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Life Cycle Assessment of an Auxiliary Power Unit system based on microtubular Solid Oxide Fuel Cell (mSOFC) for recreational vehicle applications.

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ABSTRACT

Fuel cell Auxiliary Potential Unit (APU) systems are used to produce energy when the energy is not necessary for the propulsion. The aim of using fuel cells APU systems is the reduction of atmospheric emissions, which are produced by the traditional engines.

In the SAPIENS project a microtubular Solid Oxide Fuel Cell (mSOFC) APU is developed and integrated in a camper-van in order to recharge the leisure battery.

In this study we have compared the environmental impact of the SAPIENS APU system against a conventional one, using the Life Cycle Assessment (LCA) methodology.

The results show the relevance of the use phase as contributor to the overall environmental profile together with the contribution due to the energy consumption occurring the production phase of the microtubes of the mSOFC stack and the components of the Balance of Plant (BoP).

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INTRODUCTION

This project of thesis presents a Life Cycle Assessment (LCA) study of a fuel cell APU system within the SAPIENS project.

The SAPIENS (**S**olid Oxide Fuel Cell **A**uxiliary **P**ower **I**n **E**missions/**N**oise **S**olutions) project has the aim of developing an APU (Auxiliary Power Unit) system based on the fuel cell technology, and integrate it in a camper-van, to recharge the leisure battery.

The APU (Auxiliary Power Unit) systems are used to produce energy when the energy is not necessary for the propulsion. Generally, the aim of using fuel cells APU systems is to avoid the idling of engine and, therefore, reducing the atmospheric emissions.

In the SAPIENS project it was proposed to use the Life Cycle Assessment (LCA), to achieve the sustainable product development, in order to have a better understanding of the impacts and advantages of a new fuel cell stack to be used on recreational vehicles (RVs). Another reason is the comparison of the environmental impact produced by the SAPIENS APU system and a traditional diesel idle engine, before the introduction of the product in the market.

"The Life Cycle Assessment (LCA) is an analytical tool to assist making environmentally relevant decisions concerning product systems. The scope of LCA encompasses development, production, use, disposal and recycling of products for specific applications. LCA is an established, internationally-accepted method that is defined in two ISO Standards (14040/14044)". The ISO defines as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle. [1]

The LCA procedure is regulated at the international level by the ISO rules 14040 [2] and 14044 [3], providing a standardised way to conduct the LCA. At the European level, the ILCD Handbook [4], prepared by the JRC-IES (Joint Research Centre- Institute for Environment and Sustainability), based on ISO 14040/14044, provides more details about the technical guidance for an LCA.

The standardised LCA procedure is composed of 4 fundamental steps:

1. Goal definition and scope of the analysis;
2. Life Cycle Inventory (LCI), in which all the data regarding environmental inflows and outflows of the product system are collected and the model of the system is defined;
3. Life Cycle Impact Assessment (LCIA), the evaluation of the environmental relevance of all the inflows and outflows;
4. Life Cycle Interpretation, last phase in which the results from the LCIA phase are analysed.

For the SAPIENS project LCA, Adelan (UK) and IREC (ES) jointly undertook this study to ensure accuracy. Both Adelan and IREC gathered the data and then, IREC worked to the task following the standardised approach defined for LCA studies:

1. Definition of the goal and scope of the analysis;
2. Life Cycle Inventory (LCI);
3. Life Cycle Impact Assessment (LCIA);
4. Interpretation of the results obtained.

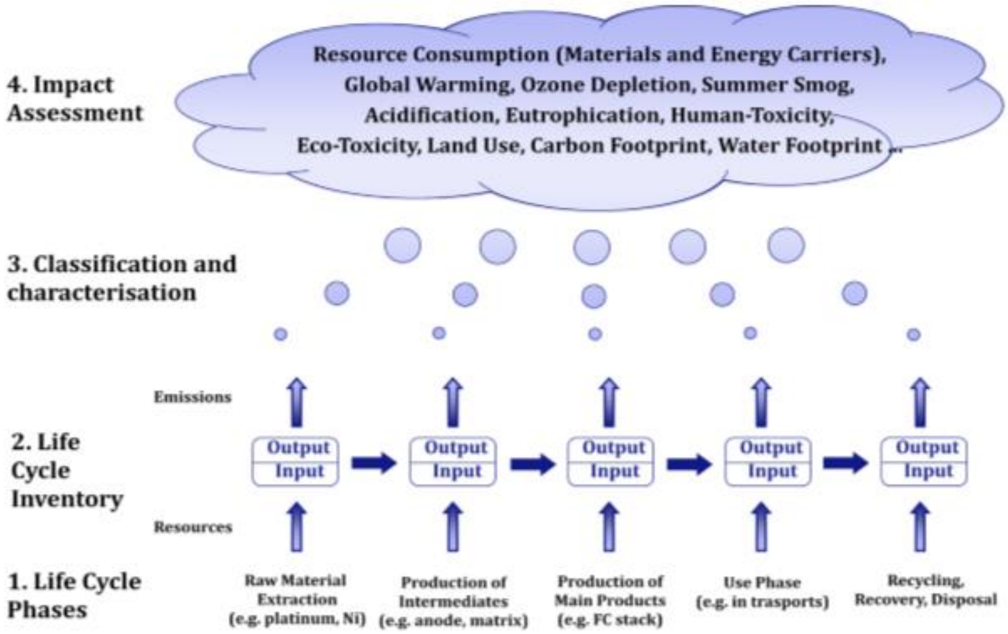


FIGURE 1 OVERVIEW OF THE LCA METHODOLOGY, FROM FC-HY GUIDE [1]

In the 1960s and 1970s the environmental issue started being of public concern, thanks to the publication of books such as “Silent Spring” (1962) by Rachel Carson and “The Limits to Growth” (1972) by the Club of Rome. In the same years in the United States the first researches related to the study of the environmental impacts of the product were carried out. They were denominated REPA (Resource and Environmental Profile Analysis) and aimed to understand and compare the life cycle of materials utilised in relevant industrial processes and analyse the energy consumption in them. One of the first companies adopting the REPA was the Coca Cola Company, with the purpose of comprehending the effects on the environment caused by several types of packaging, to make a choice regarding the most suitable materials and waste management strategy. [5]

Furthermore, the two energy crises during the ‘70s pointed out the public and politics attention on the limits of the natural resources, leading on to “sustainable development” definition, in the 1987. In fact, the United Nation’s World Commission on Environment and Development (WCED), as known as the Brundtland Commission, with its report “Our Common Future” introduced for the first time the term “sustainable development”, a type of development that “meets the needs of the present without comprising the future generations to meet their own needs” [6].

Since this mile stone of the environmental policy, more and more agreements and policy actions have been developed and performed in order to make the sustainable development happen.

Even if the LCA was not born as a tool to support the sustainable development, it has become sooner, because it “seeks to identify the possible improvements to goods and services in the form of lower environmental impacts and reduced use of resources across the life cycle stages” [7].

The term LCA (Life Cycle Assessment) was defined, for the first time, by the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990 [5].

The SETAC gave one of the first frameworks of an LCA study, comprised by 3 phases (Figure 2):

- Inventory, in which all the information and data are gathered, and the model of the system is built;
- Interpretation, where the environmental data of the inventory are linked to one (or more) specific category representing an environmental issue;
- Improvement, in which simulation about the improvement of the production are made. [5]

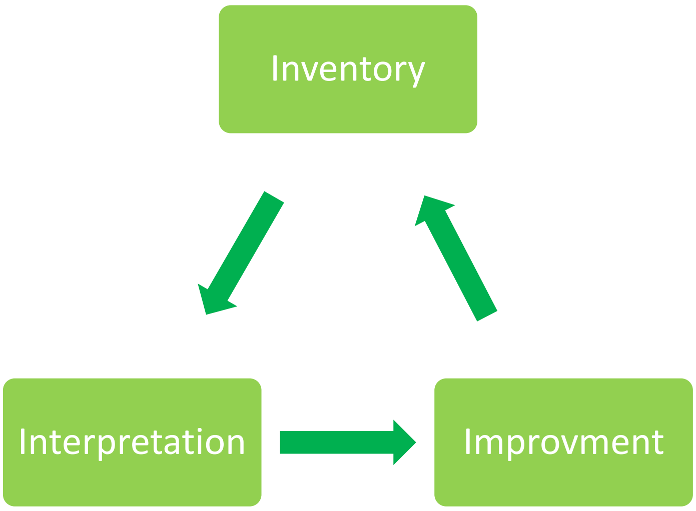


FIGURE 2 LCA FRAMEWORK PROPOSED BY THE SETAC

In the 1997 the International Organization for Standardisation (ISO) published a series of standards ISO 1404X "Environmental Management-Life Cycle Assessment" in which the framework suggested by the SETAC was enhanced. The LCA procedure was regulated by the ISO 14040, 14041, 14042 and 14043[2], providing a standardised and internationally recognised way to conduct the LCA. In the 2010, the ISOs 14042 and 14043 were revised in the ISO 14044, since then the LCA is ruled by the ISO 14040 "Environmental management-Life cycle assessment-Principles and framework" and the ISO 14044 “Environmental management-Life cycle assessment-Requirements and guidelines”.

At the European level, the ILCD Handbook [4], prepared by the JRC-IES (Joint Research Centre- Institute for Environment and Sustainability), based on ISO 14040/14044, provides more details about the technical guidance.

1.1 LIFE CYCLE ASSESSMENT STRUCTURE

The Life Cycle Assessment (LCA) “is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle” [2].

The LCA can help:

- identifying the opportunities to improve the environmental aspects of products at various points in their life cycle;
- decision-making in the industry, governmental or non-governmental organizations;
- communication and marketing sectors (for instance in the environmental product declaration and Eco-Label).

In the LCA, all the life cycle steps of the product, object of the study, are described; the description takes consideration since the extraction of resources phase until the disposal phase, going through the manufacturing, consumption/use phase.

The life cycle framework described in the ISO 14040 is comprised by 4 fundamental steps:

1. Goal definition and scope of the analysis;
2. Life Cycle Inventory (LCI), in which all the data regarding environmental inflows and outflows of the product system are collected and the model of the system is defined;

3. Life Cycle Impact Assessment (LCIA), the evaluation of the environmental relevance of all the inflows and outflows;

4. Life Cycle Interpretation, last phase in which the result from the LCIA phase are analysed.

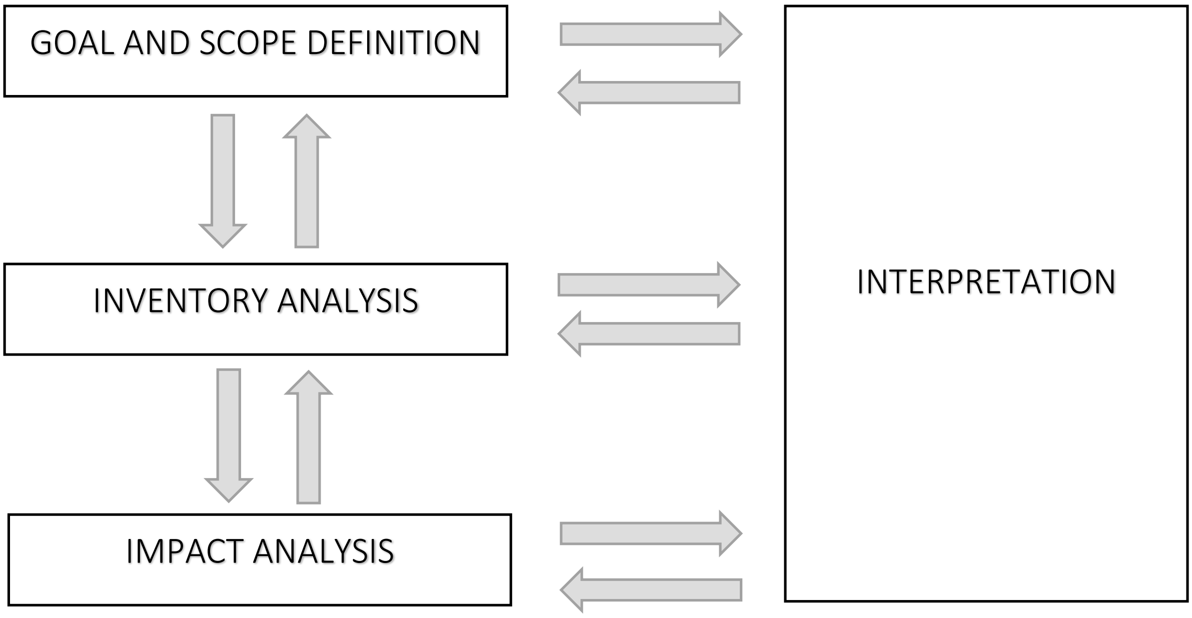


FIGURE 3 LCA FRAMEWORK SUGGESTED BY THE ISO 14040

1.1.1 GOAL AND SCOPE DEFINITION

The most important part of the LCA is the definition of the goal and scope of the analysis, this because a wrong definition could compromise the whole study.

As the ISO 14040 reports the goal and scope of the study have to be defined clearly and consistent which is the application of the study.

The goal has to define the intended application, the reasons for carrying out the study, the limitations due to the method and the intended audience, to whom the results of the study will be communicated.

The scope, that has to be in line with the goal characterises the exact system/s studied, giving the following information:

- product system to be studied;

- descriptions of functions of the system or in case of comparative study, the systems;
- functional unit;
- system boundaries, flows and cut-off criteria;
- allocation procedures;
- identification of the impact categories used in the LCIA (Life Cycle Impact Assessment) and LCIA methods applied, as well as the inclusion of normalisation and weighting;
- LCI data quality information, as the geographical and time related representativeness;
- assumptions and limitations;
- data quality requirements.

The **system** is defined as "any good, service, event or basket-of-products, average consumption of a citizen, or similar object that is analysed in the context of the LCA study" [4].

The **functional unit** (FU) is "a quantified performance of a product system for use as a reference unit" [2] to which all the inputs and outputs of the system are related. The FU is important to ensure the comparability of the LCA results, in particularly when the goal of the analysis is a comparison among two or more systems.

As the ISO 14044 reports "the **system boundary** determines which unit processes shall be included within the LCA" [3].

There are different possible system boundaries:

- *"cradle to grave"*, is the complete Life Cycle Assessment from resource extraction to use phase and disposal;

- *"cradle to gate"*, is a partial assessment from resource extraction to the factory gate, without considering the use phase and the emissions;
- *"gate to gate"*, is an assessment from the factory gate to the disposal gate (just the production phase), without considering the emissions in the environment;
- *"gate to grave"*, this is the partial Life Cycle Assessment that considers only the use and the disposal phases.

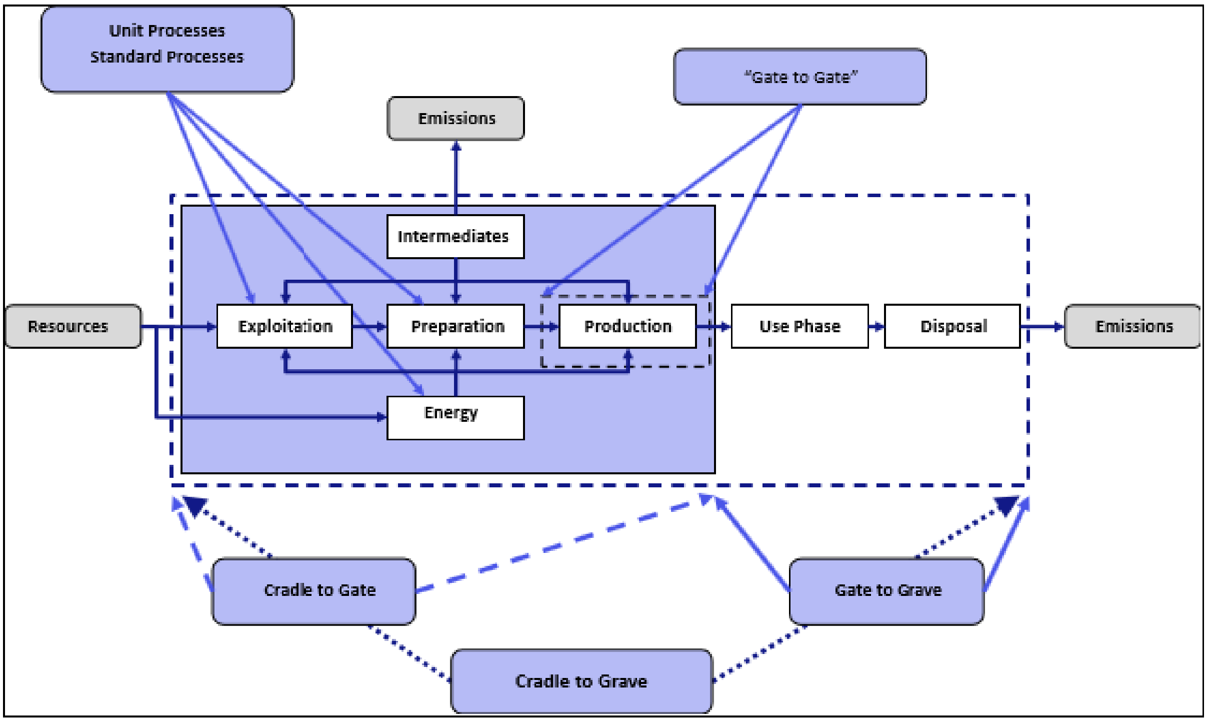


FIGURE 4 THEORETICAL OPTIONS OF THE SYSTEM BOUNDARY IN THE LIFE CYCLE OF A PRODUCT [1]

Flows are the essential elements that must be defined in order to perform an LCA. A flow is a general input or output from a process or product system.

According to what the inputs or outputs represent, three main types of flow can be defined:

- *elementary flow*, defined by ISO 14040 as " material or energy entering the system...that has been drawn from the environment without previous human transformation, or material and energy leaving the system ...that is released into the environment without subsequent human transformation" [2];

- *product flow*, which represents the product entering and leaving the system;
- *waste flow*, related to the waste leaving the process or the product system.

Every flow with a relevant impact must be included in the study. The flow relevance is given by some factors, for example the use of electricity and materials based on non-renewable resources, specific emissions and wastes, the cost of materials and energy, quantity of the materials and energy used, the use of hazardous substances, or very small quantities of materials which are essential to the total process.

Sometimes it is quite impossible or irrelevant to account for all the inputs and outputs in a process or product system. For this reason, **cut-off criteria** have to be defined and applied.

The ISO 14040 defines the cut-off criteria as “the quantity of material or energy flow or the level of environmental significance of a process or system product to be excluded from the study.”

Usually all the inputs that contribute more than 2% in weight, of the total inputs of the product system are included in the study. [1]

Allocation procedure has to be used in the case of multiple products, when the materials, energy flows and the associated environmental releases need to be associated to different products.

1.1.2 LIFE CYCLE INVENTORY (LCI) ANALYSIS

The Life Cycle Inventory (LCI) is the phase of the LCA involving the compilation and the quantification of the inputs and outputs of a system, throughout its entire life cycle.

The inputs and outputs are the flows, referring to the energy and materials necessary for the different processes included in the system boundary. Before starting the data collection process flow diagrams are usually drawn. These diagrams outline all the unit processes to be modelled including their interrelationships. Then this step, the preparation of the data collection and the steps presented in Figure 5 can be carried out.

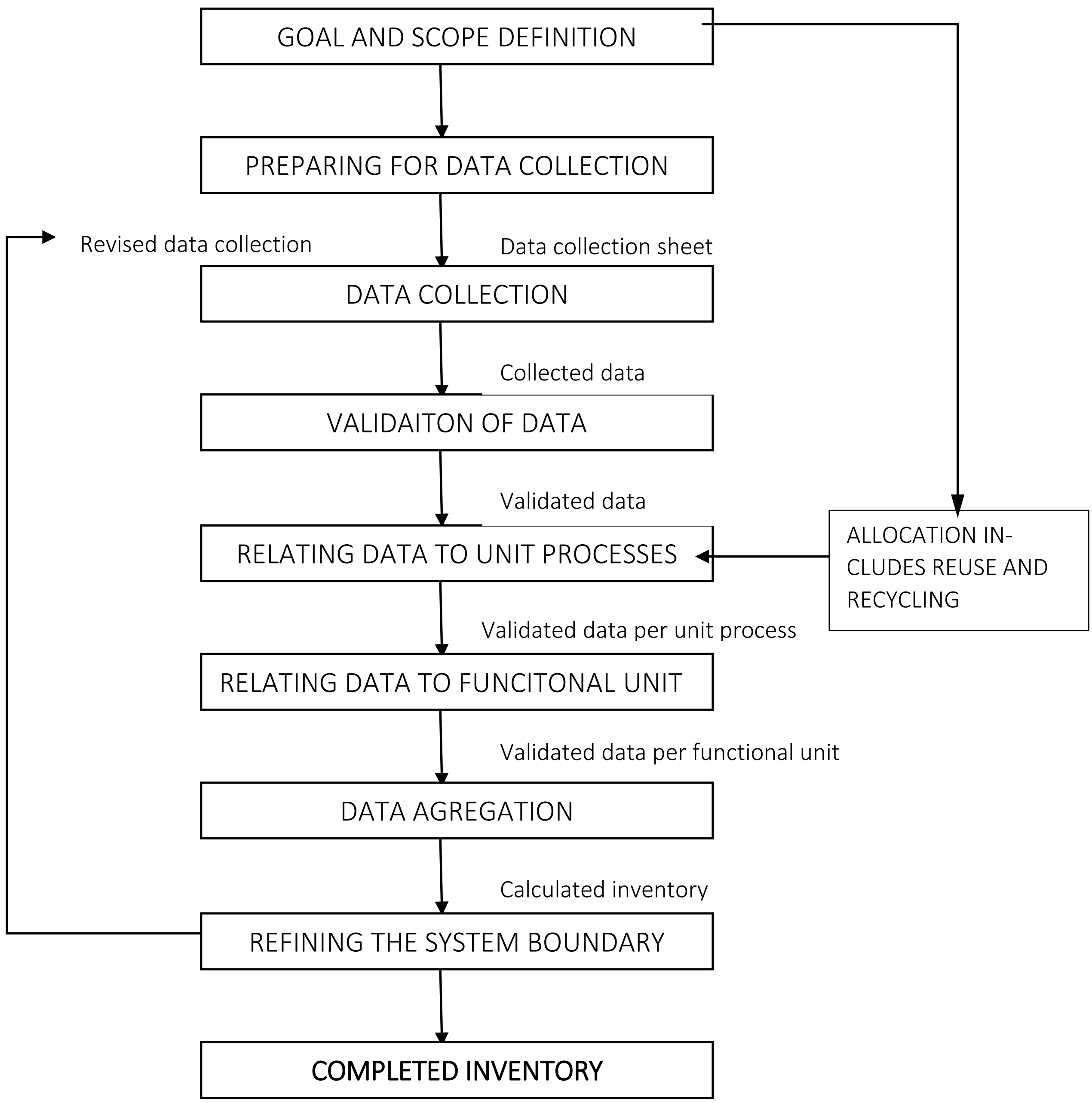


FIGURE 5 PROCEDURE FOR INVENTORY ANALYSIS [3]

The data gathered in the LCI phase can be qualitative or quantitative and be primary or secondary data.

The primary data are the ones coming from direct measured at the operated processes, instead the secondary data are the ones from scientific literature, technical sheets and/or databases.

Finally, all the data gathered will be used to calculate the inputs and outputs of each processes unit.

All the inputs and outputs of each unit process have to be referred to a **reference flow**, that is a "measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit" [3].

It means that in all the flows of the system will be calculated for satisfying and being relating to the functional unit.

Once that the calculation of the flows have been accomplished a reviews of the data with the applications of the cut-off criteria can be performed and then, if necessary, a re-definition of the system boundary can be done.

1.1.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The Life Cycle Impact Assessment (LCIA) phase intends to understand and evaluate the magnitude and significance of the potential environmental impacts. The results of LCIA are indicators of potential environmentally relevant impacts, not a prediction of actual environmental effects.

All the inputs and outputs elementary flows of the LCI are translated into impact indicator results concerning human health, natural environment and resource depletion. As written in the FC-Hy Guide [1] in the LCIA phase "each flow of LCI is grouped in one or more categories. Within each category, the flows are aggregated using equivalence factors called characterisation factors. These factors are based on the physical and chemical properties of the impact-causing substances, as well as on the fate of the flows once they leave the product system towards the environment. The aggregated value is called "potential impact" and is most commonly given in kg equivalent of a certain reference substance for the respective category."

The LCIA phase must include the following mandatory elements:

- selection of impact categories, category indicators and characterisation model;

- classification that is the assignment of LCI results to the selected impact categories;
- characterisation that is the calculation of category indicator results.

The impact categories are classes representing environmental issues to which the results of LCIA may be assigned.

This means more environmental issues (emissions) can fall into one impact category.

There are 2 main types of categories:

- *midpoint categories* requiring modelling the impact using an indicator located along the impact pathway, examples Global Warming Potential (GWP), Acidification Potential (AP) and Resource Depletion;

- *end-point categories* identified such as attribute or aspect of natural environmental, human health or resources that highlight environmental issues giving cause of concern.

Endpoint categories require an extensive modelling all the way to the impact on the Areas of Protection (AoP) entities, such as human health, natural environment and natural resources.

The endpoint models are easily interpreted, because of they are more related to what matters to society, and could be used for external communication, even if the uncertainties associated are higher.

The midpoint modelling allows an easier identification of the contribution of different processes, and can be achieved quite accurately.

In the European Parliament and Council published “The Sixth Environment Action Program of the European Community 2002-2012” (European Parliament and the Council 2002) the basis for the choice of the impact categories is considered. Figure 3 shows the framework of the LCI as defined in the “FC-Hy Guide” [1]. The environmental priorities within this program are:

- Climate change;
- Nature and biodiversity;
- Environment, health and quality of life;
- Natural resources and wastes.

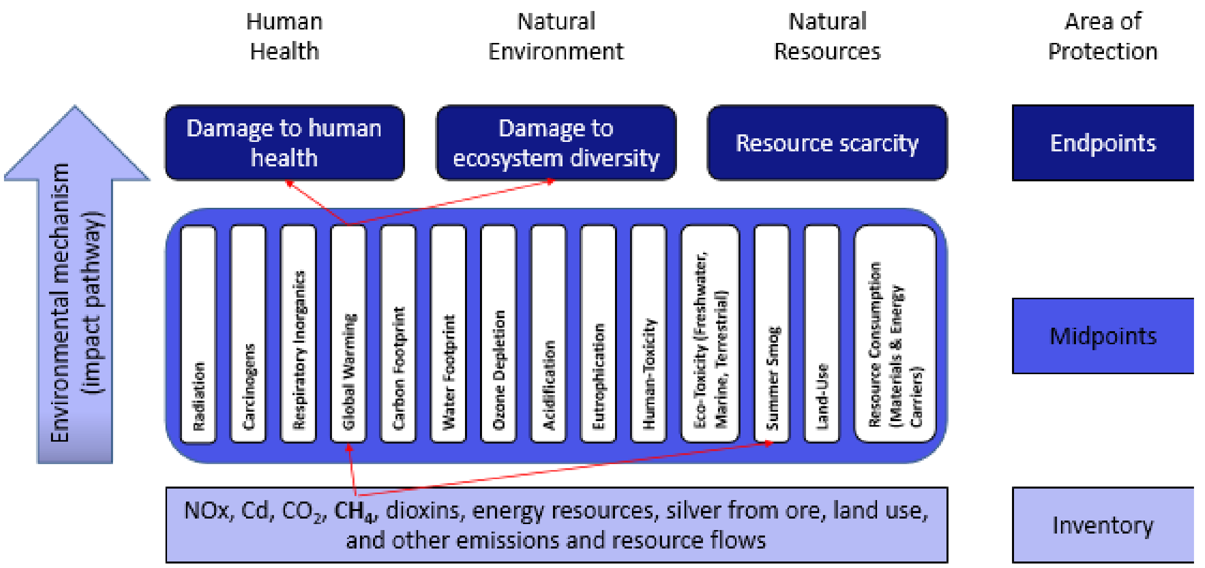


FIGURE 6 SCHEMATIC STEPS FROM THE LIFE CYCLE INVENTORY TO IMPACT CATEOGORY, FROM FC-HY GUIDE [1]

According with the "FC-Hy Guide" [1] this study will be used the following midpoint impact categories:

- Global Warming Potential (GWP);
- Acidification Potential (AP);
- Abiotic Depletion (AD);
- Eutrophication Potential (EP);
- Ozone depletion potential;
- Human toxicity.

There are several different Life Cycle Assessment methods with the major difference being whether they are midpoint or endpoint oriented: CML, ReCiPe, LIME and IMPACT 2002+.

Optional elements of the LCIA phase are normalisation, weighting and the data quality analysis.

The **normalisation** is the calculation of the impact category results relative to a common reference, by dividing the indicator results by the respective reference value, or normalisation basis.

The normalisation basis is typically the impact or damage results per capita of a total annual territorial elementary flows in a country, region, or continent, or globally.

In **weighting** each of the normalised, or not, indicator results for the impact categories are multiplied by a specific weighting indicator, that reflects the relative relevance of the different impact categories among each other.

The **data quality analysis** allows understanding the reliability of the data. Usually the *sensitivity analysis* and the *uncertainty analysis* are carried out to accomplish this step.

1.1.4 LIFE CYCLE INTERPRETATION

The Life Cycle interpretation of the LCI and LCIA has the aim to:

- identify the relevant issues based on the results of the LCI and LCIA;
- evaluate the sensitivity, uncertainty and consistency checks;
- draw the conclusions of the study, identify the limitations and make some recommendations.

A fuel cell is a device generating electricity by electrochemical reactions, it converts the chemical energy stored in the fuel in electricity.

As some reported the principle of the fuel cells was discovered by a German chemist named Christian Friedrich Schönbein, that explained the concept of hydrogen fuel cells introduced for the first time by Sir William Robert Grove.

"Grove discovered that by immersing two platinum electrodes on one end in solution of sulphuric acid and the other two ends separately sealed in containers of oxygen and hydrogen, a constant current was found to be flowing between the electrodes. Sealed containers contained water together with the respective gases. Grove noted that the water level rose in both tubes as the current flowed." [8]

Therefore, a fuel cell is made up by three fundamental elements: an anode, an electrolyte and a cathode.

At the anode the fuel oxidation occurs by using a catalyst, usually the fuel is hydrogen that is turned in a positive ion and in an electron.

The electrolyte is a substance designed to let the ions pass through itself, but not the electrons, that will travel through a wire to create electric current. When the ions and the electrons will reach the cathode they will react with the oxygen to create water.

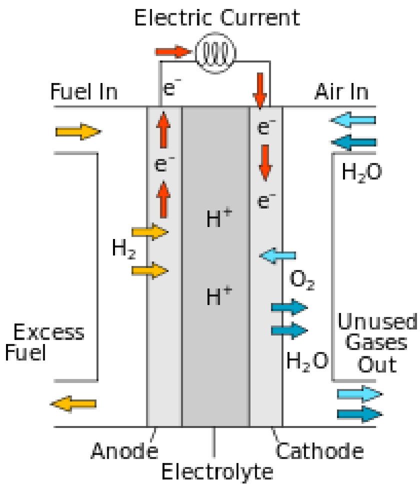


FIGURE 7 SCHEME OF THE PROTONS CONDUCTION IN A FUEL CELL

Since the time of Grove and Schönbein a lot of developments have been made and several types of fuel cell systems have been investigated and improved.

In the 20th century Emil Baur (1921) built the first molten carbonate fuel cell, instead in 1933 Thomas Francis Bacon developed the first fuel cell made of hydrogen and oxygen with practical use, and then he begun investigating alkaline fuel cells and following, in 1958 he presented to the Britain's National Research Development Corporation an alkaline fuel cell with electrodes of 25.4 mm in diameter.

In 1961, G.V. Elmore and H.A. Tanner made known a phosphoric acid fuel cell, in which the electrolyte was made of a mixture of 35% phosphoric acid and 65% of silicon dust.

Nowadays, four principal types of fuel cells are known [9]:

1. *Proton Exchange Membrane Fuel Cells* (PEMFCs) in which the electrolyte is a polymeric membrane and the electrodes are metal based. They work at a temperature around 100°C and due to this can only work using pure hydrogen;
2. *Phosphoric Acid Fuel Cells* (PAFCs) have a phosphoric acid as electrolyte and work at a temperature between 150-200°C. They are quite resistant to poisoning by carbon monoxide, but tend to have a lower efficiency than the other type of fuel cells in the production of the electricity;
3. *Solid Oxide Fuel Cells* (SOFCs) are characterised by a solid ceramic electrolyte, made of Yttrium Stabilised Zirconium (YSZ). They require higher operating tem-

peratures around 700-1000°C, which means a possible reforming of the fuel by the fuel cell itself, with the possibility of using different types of fuel and without the needing of an external reforming.

4. *Molten Carbonate Fuel Cells* (MCFCs) have an electrolyte made of a molten carbonate salt suspended in a porous ceramic matrix. As the SOFC they work at high temperature around 650°C, so they can operate with different fuels (methane, natural gas) with no needing of an external reformer.

2.1 SOLID OXIDE FUEL CELLS

Solid oxide fuel cells, as the name suggests, are fuel cell comprised by a solid electrolyte made of solid ceramic material. The most used and diffused materials for the electrolyte layer is a zirconium oxide stabilized with yttrium oxide, named Yttrium Stabilised Zirconium (YSZ).

Due its features this type of fuel cell needs high temperature of operation, around 600ºC up to 900ºC, that could be seen as a limit for its applications, due to the necessity of using robust, heat-resistant materials for the BoP system and stack. Despite that the high operating temperature is also a point of strength, because it improves the kinetic of the reaction allowing avoiding the use of metallic catalyst and, at the same time, provides the right environment for reforming the fuel within the fuel cell itself, without needing for an external reforming.

Nowadays, the SOFCs are built in two different shapes: planar and tubular.

The planar SOFCs are comprised of cell repeat units, one on the other. Each cell repeat unit is formed by 4 layers: interconnection, cathode, electrolyte and anode.

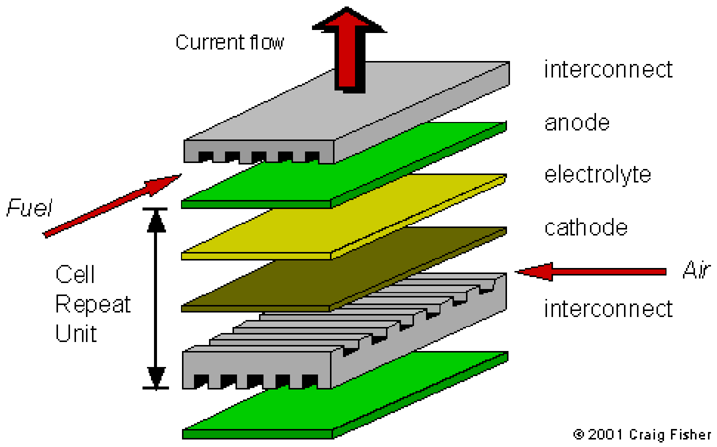


FIGURE 8 SCHEMATIC PLANAR DESIGN FOR SOFC

Instead, the tubular configuration presents three concentric layers: anode, electrolyte and cathode. The interconnections and current collector may have several configurations.

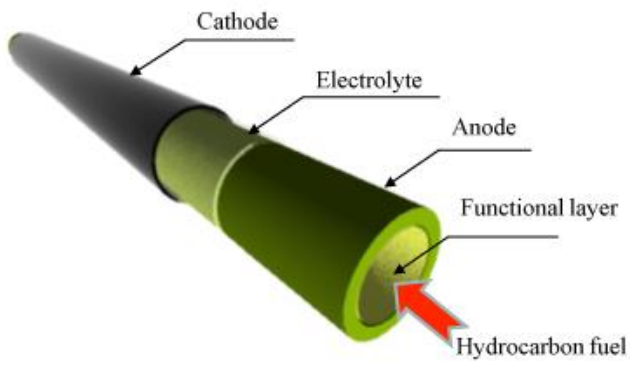


FIGURE 9 BASIC DESIGN FOR mSOFC

2.1.1 TUBULAR SOFC

"The tubular solid oxide fuel cells (SOFCs) were pioneered in the 1960s, becoming commercially available in the 1970s, when Westinghouse began to use an electrochemical vapour deposition technique for their fabrication. This design reduced the problems of brittleness and sealing as compared to planar cells, but still required a heat up time of 4-6 hours. Whilst their performance was good, with single cells exceeding 20000 hours of operation, they did not have a high power density (only around 0.6 W cm^{-3}; around half that obtained for planar cells at the time). For tubular cells, power density depends upon the inverse of cell diameter; the narrower, the better the performance." [10]

This observation led the invention of the micro-tubular SOFC by Professor Kevin Kendall and Dr Michaela Kendall in the early 1990s. The first mSOFC tubes were based on electrolyte extruded tubes of YSZ with a diameter up to 5 mm and the wall thickness between 100-200μm.

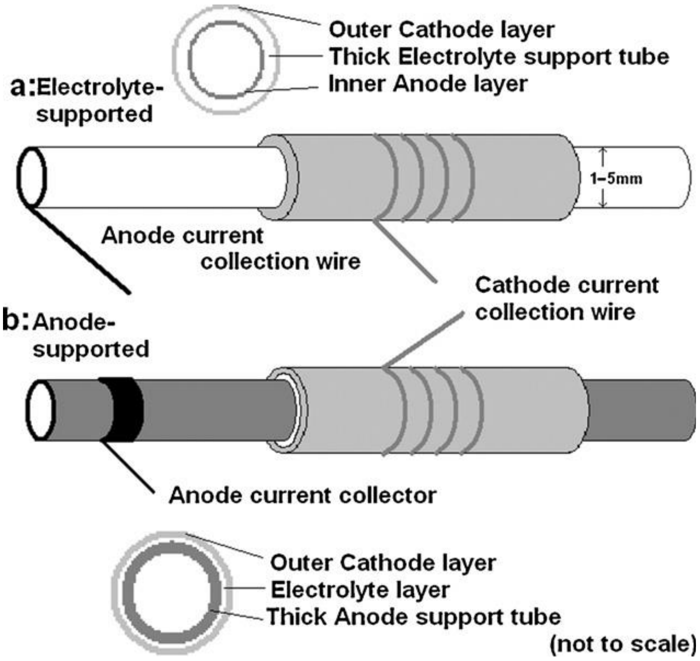


FIGURE 10 BASIC mSOFC DESIGN [10]

Both the anode and the cathode based cells have the support tube longer than the active cell, this because an inactive termination of the tube is used as inlet gas tube, and the other as combustor tube, where the fuel and oxidant combine. [10]

Nowadays, the most used configuration is the one based on the anode, having layers very thin of the μ-metres order and, as a consequence of it a lower Ohmic resistance.

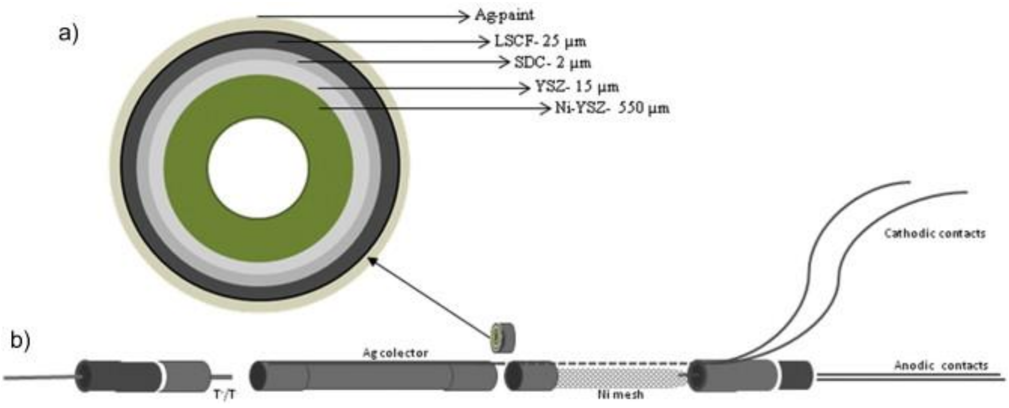


FIGURE 11 SCHEME OF (A) THE CROSS SECTION OF THE MT-SOFC LAYERED STRUCTURE AND (B) THE SETUP CONFIGURATION FOR PERFORMANCE AND ELECTROCHEMICAL CHARACTERIZATION, FROM [11]

The common fuel used is hydrogen, that it can be produced by several reforming processes:

1. Steam reforming of natural gas (methane);
2. Thermochemical water spitting;
3. Gasification;
4. Partial oxidation;
5. Photolysis;
6. Electrolysis. [12]

Using the tubular SOFC it can be use an internal reforming of the natural gas without needing another system for the production of hydrogen. [13]

In fact, with the internal reforming when the fuel enters in the tubes (at the anode) it is converted in hydrogen; at the cathode the molecules of oxygen are ionised and the oxygen ions go through the electrolyte layers, while the electrons are collected by the current collector wires. When the oxygen ions arrive at the anode react with the hydrogen to produce water. In a real scenario of internal reforming water is not the only product of the reaction, indeed, carbon monoxide and carbon dioxide, with other not reformed hydrocarbons are present, in small quantities.

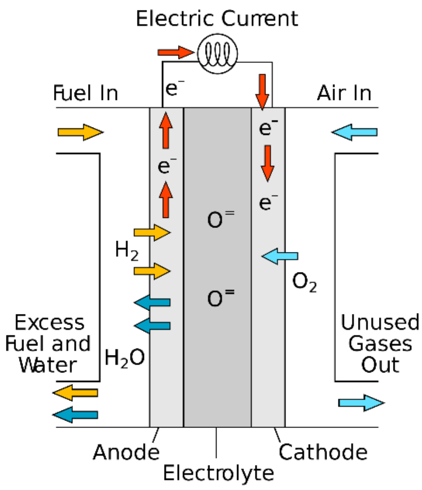


FIGURE 12 SCHEME OF THE PROTONS CONDUCTION OF A SOFC

2.2 SAPIENS PROJECT

The Solid Oxide fuel cell Auxiliary Power In Emissions/Noise Solutions (SAPIENS) project has the aim to design, optimise and build several microtubular Solid Oxide Fuel Cell (mSOFC) stacks and integrate them into hybrid power systems consisting of a fuel cell stack and a battery. These will form auxiliary power unit (APU) to provide power, between 80-100 W, for the appliances found in a recreational vehicle (RV).

The SAPIENS project is found by the European Union, particularly by the Fuel Cell and Hydrogen-Joint Undertaking (FCH-JU), a public private partnership supporting research, technological development and demonstration activities with the aim of accelerating the market introduction of these technologies.

FIGURE 13 RECREATIONAL-VEHICLE (RV)

The Consortium partners of the SAPIENS project are private companies, universities and research institutes spread all over the Europe, such as Adelan Ltd., Auto-Sleepers, Centre for Abrasives and Refractories Research & Development (C.A.R.R.D.), CUTEC Institute, Joint Research Centre-Science (JRC), Catalonia Institute for Energy Research (IREC) and West Pomeranian University of Technology (ZUT).

The SAPIENS APU system is based on core technology developed at Adelan Ltd., a UK based fuel cell technology company.

All the Consortium partners have been working to improve the tubes performances, develop a stack and a Balance of Plant to ensure the production of energy for satisfying the RV energy request.

The Balance of Plant (BoP) is comprised of all the additional components, such as gas processor to clean the fuel, plus the other equipment for electrical and mechanical control.

The fuel to be used in the power cell is liquid petroleum gas (LPG), also known as autogas, which is widely used in the leisure industry for RV appliances, such as cookers, fridges and water heaters. The power cell must be able to operate on commercially available LPG obtainable from garage forecourt pumps, or bottled Propane or Butane gas available at camping outlets globally. Another reason for the choice of LPG as fuel is because of its superior energy density compared to methanol.

The mSOFC was chosen because it can convert LPG in a portable unit, capable of rapid start-up, while also providing low noise and low emissions.

The maximum dimensions of the complete power cell, including ancillary items and the control system, should be similar to a leisure battery, approximately 300x200x150mm or equivalent volume of 9.0 litres. The weight should not be more than 20 kg. [14]

The scientific literature about LCA for SOFC fuel cells APU is not so vast like for others subjects, much less it is the scientific literature concerning the LCA for APU systems based on microtubular SOFC.

However, there are relevant and interesting studies that allow us a first understanding of the system and the gaps of the data, which could be present.

In the 2000 the Imperial College published an extensive study titled "Environmental emissions of SOFC and SPFC" [15], in which, using the LCA approach, it was tried to understand the wastes and the emissions to the environment generated from the manufacturing and the use of SPFC (Solid Polymer Fuel Cell) and planar and tubular SOFC.

Karakoussis [16] analysed the potential environmental impacts of a planar and a tubular SOFC systems. The study disclosed that in a planar SOFC APU the majority of the emissions are related to the stack components, instead in a tubular SOFC the main amount of emissions are caused by the components of the Balance of Plant (BoP).

Others studies, like the series written by Baratto and Diwekar [17] [18] [19] are focused on the fuel cells used in APU systems. In the paper "Life cycle assessment of fuel cell-based APUs" [19], the two scientists compared an APU system based on SOFC and a diesel engine. They assessed the human health and environmental impacts of the systems; the results of the comparison show a lower total amount of pollutants emitted from the SOFC respect the idling of diesel engines, and, in all the health risk assessment categories, several orders of magnitude of difference between the idling of diesel engines and SOFC based-APUs. The more relevant differences between the systems is in the cancer risk, that as Baratto and Diwekar reported, is mainly due to the high emission of particulate matter (PM_{10} and $PM_{2.5}$) and the realise of benzene and aldehydes by the diesel engines.

Another study of the Department of Chemical Engineering of the University of Birmingham highlights the energy and carbon payback times for the SOFC used in domestic CHP (Combined heat and power) [20]. The research compares, using the LCA methodology, a planar SOFC based domestic micro-CHP (1 kW) and the traditional technologies presenting in the UK. The results revealed that the electricity and the chromium for the stainless steel components carry the highest contributions to the carbon footprint. The carbon payback time of the SOFC system results being a little more than a year, during which the system can save the same amount of CO_2 emitted during its construction. Instead the energy payback time has been estimated being roughly of 2 years.

In the 2007 a study about the potential fuel consumption and emissions from a SOFC APU using diesel [21] showed the economic and environmental benefits from using the SOFC APU on long-haul trucks. As the authors wrote “replacing engine idling with the fuel cell APU would result in a mean 80% improvement of fuel consumption during the stationary portion of the cycle for all trucks with avoidable idling. The 90% confidence interval for the trials was from 59% to 94% reduction in idled diesel use” [21]. Of course the kind of fuel used is more relevant and the use of another fuel like methane instead of diesel in the SOFC APU might reduce more the emissions and the costs.

Common denominator of all these studies, and others, is the lack of information regarding the manufacturing processes of the fuel cells and their End-of-Life management.

Both problems are present because the product is not yet ready for the market and the companies are trying to get it ready. This means a continuing research to improve the efficiency, understand the right conditions of manufacturing and the right composition of the materials.

The concern about the end of life management comes from the new materials used in the fuel cells systems, presenting a new challenge and the need to be fully understood before a wide commercialisation.

Those problems mean a difficult for LCA practitioners, as reported in [19] “the life cycle inventory data for production of some of the key ceramic materials is particularly uncertain at present”. So at the present knowledge to run a LCA study it has to be done some analogies with other materials, of which the data of production and the environmental information are known.

4 LCA ANALYSIS

This chapter is going to present the entire work of the Life Cycle Assessment study, following, not completely, the framework and the guidelines of the ISO 14040 [2] and ISO 14044 [3].

4.1 DEFINITION OF THE GOALS AND SCOPE OF THE STUDY

This LCA study is performed in order to compare the environmental impact through the entire life of the fuel (auto-gas) and fuel cell system based APU from the SAPIENS project [14] with a traditional technology.

The main goals of the study are:

- analyse and compare the potential environmental impacts of the fuel cell and the traditional system built on the RV;
- identify key improvement opportunities in the production chain for an optimal recyclability and minimal resource consumption of APU for Recreational Vehicles (RVs);
- understand the benefits that may been using a fuel cell system for producing electricity;
- study the possible “end of life management” of the fuel cell system.

4.1.1 FUNCTIONS, FUNCTIONAL UNITS (FU) AND REFERENCE FLOWS

For the fuel cell system under study, the main purpose is the production of electricity, so the functional unit is defined as the production of energy during the entire life of fuel cell system.

Since the efficiency of the entire system is around 40%, the functional unit has been estimated equal to 450 MJ, the quantity of electricity required in a trip scenario of 3000 hours (125 days) to satisfy the electricity demand of a RV during a year. [22]

4.1.2 SYSTEM BOUNDARY, FLOWS AND CUT-OFF CRITERIA

For a complete impact assessment of the new implementing mSOFC system, it was decided to use the **system boundary** “cradle to gate”. Applying this system boundary means taking account of:

- the production of raw materials uses in the tube manufacturing;
- the energy consumption in the system production phase;
- use and consumption of the product;
- End-of-Life that is the final stage of the life cycle study. In this step the environmental impact associated to the final disposal, including the transport to the final destiny of the wastes.

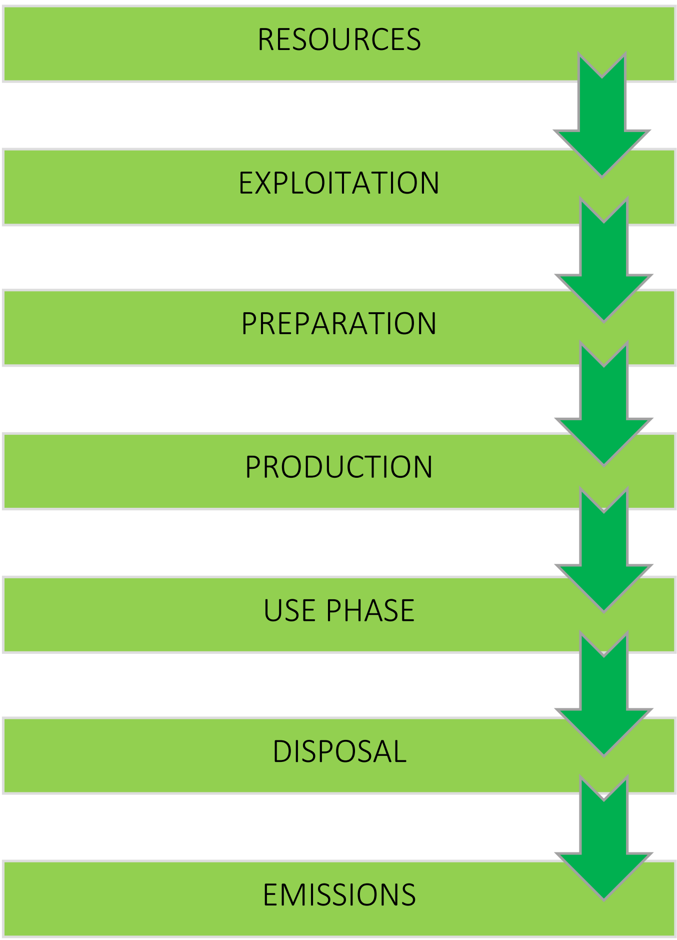


FIGURE 14 SCHEME OF THE PORCESSES CONSIDERED IN THE LCA STUDY

It does not include:

- the energy and the material inputs required to manufacture the equipment used in the production of the fuel cell system;
- the transport;
- the components that are in common with the conventional battery-powered system.

Considering that the principal aim of this study is to compare the traditional APU system used in the RVs and the mSOFC APU system developed in the SAPIENS project, as it has pointed out it has been decided to eliminate from the study (and therefore kept as out the boundaries) the impact of the same or similar elements present in both systems.

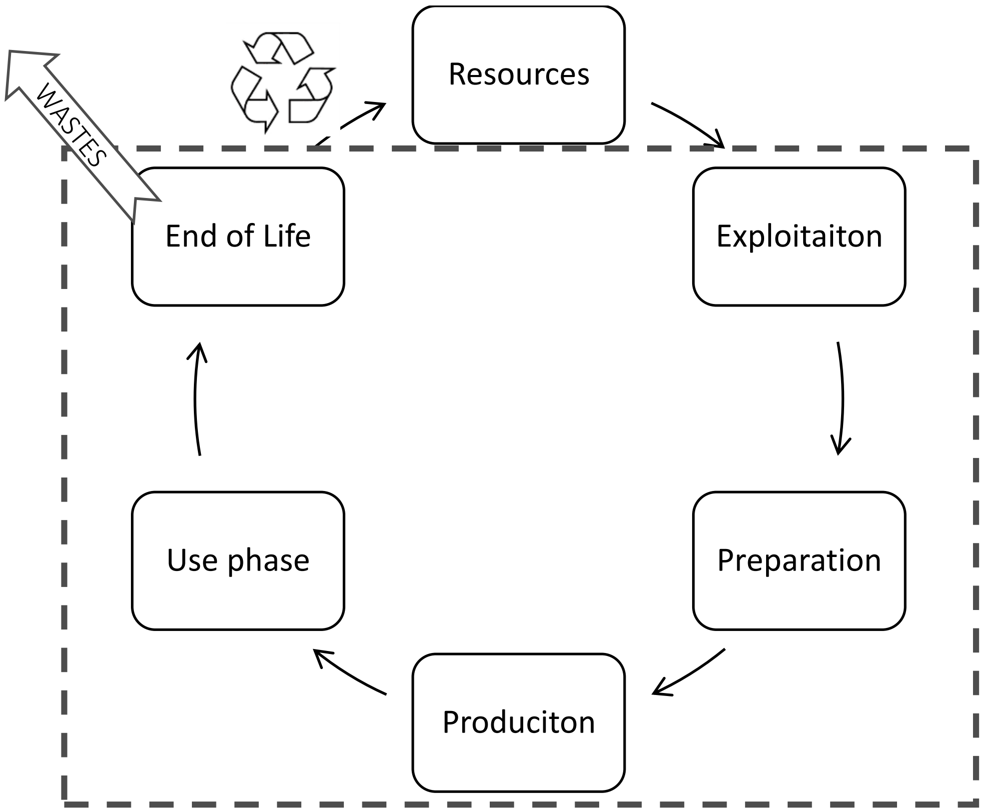


FIGURE 15 SAPIENS SYSTEM BOUNDARIES

The **Flows** are the essential elements that must be defined in order to perform an LCA. A flow is a general input or output from a process or product system.

Each flow with a relevant impact must be included in the study. Flows for the SAPIENS mSOFC APU system are summarised in Table 1.

Unit of product	Components	Inputs	Outputs
Microtubular fuel cell	Anode, cathode, elec-trolyte	Raw powders, ancillary materials dur-ing the manufacturing processes, electricity	Atmospheric emissions, Waste
Assembled stack	Tubes, interconnection materials (metal com-ponents), recuperator, insulation, other	Materials (steel, alumi-na, silver, platinum, ru-thenium)	
Assembled system	Above inputs, BoP	Above inputs, materials (plastic, steel, copper, teflon, PVC), sulphur trap, electricity	Atmospheric emissions, waste
System assembled- op-eration phase	Above components	Fuel consumption, sul-phur trap powder	Combustion emissions, wastes from the sul-phur trap
End of life	Above components		Waste

TABLE 1 DEFINITION OF THE mSOFC APU SYSTEM RELEVANT FLOWS CONSIDERED IN THE LCA STUDY.

All the inputs that contribute more than 2% in weight, of the total inputs of the prod-uct system are included in the study.

4.1.3 MAIN ASSUMPTIONS AND DATA SOURCE

To proceed with the inventory and the calculation some assumptions have been made.

- The only factor for evaluating the conventional idle diesel engine system is the *diesel life cycle*. Since the internal combustion engine will still be used mainly for the propulsion of the RV.
- Due to the irrelevant weight and their compositions it has been decided to cut off the pressure sensors and the K-thermocouples.
- The tubes modelling considers the exceeding material used for the production of the tubes selves (estimating in 5% additional of the effective weight of the tubes) to justify the estimated losses of materials occurring in this phase.

- For the electricity supplying it has assumed that all the production and waste management is located in Europe, hence the European electricity mix (EU-27, 2011) has been adopted.
- For the transport to the end of life facilities it has supposed to use an Euro 4 diesel truck trailer, with a 12.4 t of payload capacity. Distances for transport of materials have been set equal to 100 km, outbound and return.
- For the fuel consumption of the SAPIENS system only a 30 minutes start-up cycle, using 0.5 kg of LPG, has been counted.
- The emissions of gas from the LPG combustion to the atmosphere are calculated using the stoichiometric reactions of a LPG mix at 70% propane and 30% butane.

Primary data relating to the tubes manufacturing, hotbox and BoP components and materials have been provided by Adelan Ltd., C.A.R.R.D. and CUTEC as project technology partners, and refer mainly to the 2014 development.

Secondary data about the BoP components have been obtained from CUTEC and product datasheets. For the secondary background data, commercial database, such as GaBi Professional database from Thinkstep and Ecoinvent 2.2, have been used.

4.1.4 IMPACT CATEOGORIES AND LCIA METHOD SELECTION

For the study it was used the CLM 2001, updated in April 2013, impact method developed by the Institute of Environmental Science (CLM) at Leiden University [23]. The impact categories have been selected following the suggestions of the “FC-Hy Guide” [1] for fuel cells LCA studies.

- **Acidification Potential** (**AP**) caused by the release in the environment of substances such as sulphur oxides, nitrogen oxides, inorganic acids and ammonia, which can produce acid rains with the release of acid ions in the water and in the soil. The AP is expressed as kg SO_2 equivalents/ kg emission.

- **Global Warming Potential** (**GWP**) expresses the contribution to the raise of the greenhouse effect, that is a natural effect allowing the life as we know it on the

Earth. The continuous emission in the atmosphere of greenhouses gases, such as CO_2, CH_4, N_2O and O_3, make the greenhouse effect increasing, that means a rise in the temperature. The GWP represents a factor for time horizon of 100 years and it is expressed in kg carbon dioxide/kg emission.

- **Eutrophication Potential** (**EP**) includes all the impact derived from excessive emissions of nutrients in the aquatic environment leading to a fast and huge growth of the aquatic population over the environment carrying capacity causing a deterioration of the water quality, a reduction of the population and of the value of the utilisation of the aquatic ecosystem. The EP factor is expressed in kg PO_4 equivalents/ kg emission.
- **Abiotic Resource Depletion Potential, elements** (**ADP-elements**) [kg antimony equivalents/kg]: extraction the depletion of abiotic resources concerns the protection of the human welfare, human and ecosystem health, the factor depends from the minerals extraction, and it is an scarcity index of the resource.
- **Abiotic Resource Depletion Potential, fossil** (**ADP fossil**) is expressed in MJ and gives information about the scarcity of fossil fuels.
- **Photochemical Ozone Creation Potential** (**POCP**), or photo-smog is created by the degradation of VOC (Volatile Organic Compounds) and nitrogen oxides (NO_x) emitted in the lower tropospheric layer by the natural, and mostly, anthropogenic processes. These compounds in presence of light degrade themselves and chemical reactions forming ozone (O_3) that is a toxic substance for the humans, animals and for the vegetation. The factor POCP is expressed as kg of ethane equivalents.
- **Ozone Depletion Potential** (**ODP**) is a factor referring to the potential decomposition of the ozone layer in the stratosphere. Its decomposition is due to the halocarbons (CFCs, HCFCs, halogens etc.) released in the atmosphere by the anthropogenic processes. This factor is expressed as kg CFC-11 equivalents/ kg emission.

- **Human Toxicity Potential** (**HTP**) human toxicity concerning effects of toxic substances on the human environment, the characterisation factor is called and it is expressed as 1,4-dichlorobenzene equivalents/ kg emission.

- **Freshwater Aquatic Ecotoxicity Potential** (**FAETP inf.**) [kg DCB equivalents] is referring to the impacts of toxic substances on freshwater ecosystems. The total emissions are evaluated in terms of benzene equivalence (carcinogens).

- **Marine Aquatic Ecotoxicity Potential** (**MAETP**) [kg DCB equivalents] is referring to the impacts of toxic substances on marine ecosystems. The total emissions are evaluated in terms of benzene equivalence (carcinogens).

- **Terrestrial Ecotoxicity Potential** (**TETP**) [kg DCB equivalents] is referring to the impacts of toxic substances on terrestrial ecosystems. The total emissions are evaluated in terms of benzene equivalence (carcinogens).

- **Primary energy from renewables and non-renewables resources, net calorific value** [MJ] is the total amount of energy consumed in the system. It takes account of the fossil and renewable origin of any type of energy used in the system.

4.1.5 SYSTEM DESCRIPTIONS: SAPIENS VS CONVENTIONAL SYSTEM

The **SAPIENS system** is developed with the aim to produce energy to be stored in a battery, to be used in the domestic applications of the RV. Usually the traditional system does not allow long stops without be dependent by camp-site, where it is possible recharge the battery, or without moving the RV.

The system, developed in the SAPIENS project, will recharge the leisure battery of the RV anywhere and anytime.

The fuel used is Liquid Petroleum Gas (LPG or Autogas), that is widely available at fuelling stations throughout Europe. This kind of fuel is a mix of liquefied propane and butane gases. On the camper-van the fuel is stored in a tank, usually containing 10 or 15 kg, up to a maximum of 20 litres. For this study it was assumed the quantity of LPG stored in the tank is 20 litres.

The Auxiliary Power Unit (APU) developed is composed essentially of 3 parts:

1. "Hot box", including the mSOFC stack, where the chemical energy stored in the fuel is converted in the electrical energy;
2. Balance of Plant (BoP), including the electrical devices that work to control the energy production by the stack;
3. Leisure battery for RV.

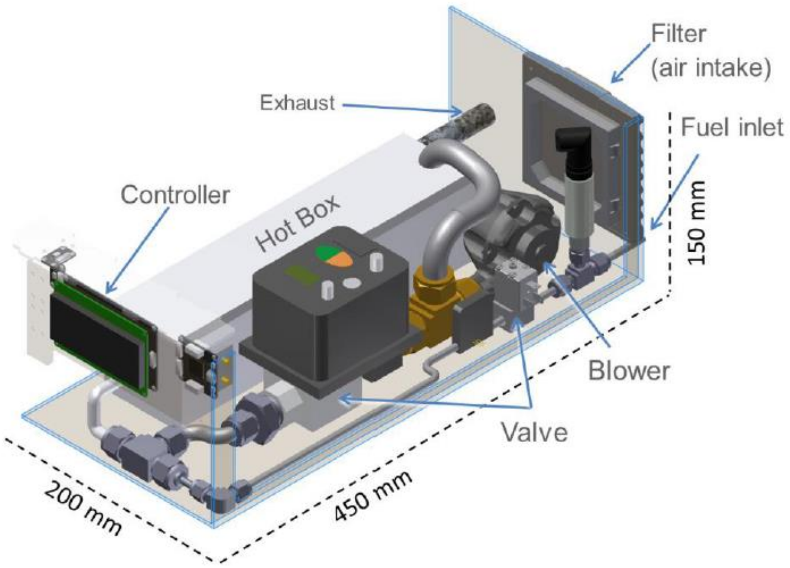


FIGURE 16 PACKAGING CONPEPT FOR APU SAPIENS SYSTEM (DATE: 03/2014)

Essentially the system uses air and fuel that is previously purified from the sulphur components, then the chemical energy stored in the fuel is converted into electrical energy through electrochemical reactions.

The components contained in the "hot box" are:

- mSOFC tubes;
- silver wires;
- tubes manifold;
- reformer;

- afterburner;
- recuperator and metal heat exchanger;
- insulation.

The components of the BoP are:

- temperature sensors;
- pressure sensors;
- air blower;
- flow meters, to adjust the air and fuel rate;
- valves;
- sulphur trap;
- µ-PC and controller hardware;
- converter;
- tubing;
- case.

All these components work to perform in the right way, at the right environmental conditions.

In the mSOFC, the hydrogen is produced inside the tubes using the natural gas (propane or butane), through the Catalytic Partial Oxidation (CPOx). The hydrogen is then used as fuel inside the tube, to produce energy.

For the SAPIENS APU, CPOx occurs inside each tube, in order to save space, using a metal catalyst plug.

Below we list the reactions occurring with LPG fuel, a mix of propane and butane (70% propane and 30% butane).

CPOx (catalytic partial oxidation)	$C_3H_8 + 1.5O_2 \rightarrow 3CO + 4H_2$ (propane)
	$C_4H_{10} + 2O_2 \rightarrow 4CO + 5H_2$ (butane)
ANODE (oxidation reaction)	$H_2 + 0.5\ O_2 \rightarrow H_2O$
	$CO + 0.5\ O_2 \rightarrow CO_2$
COMPLETE REACTIONS	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$ (propone)
	$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$ (butane)

TABLE 2 STOICHIOMETRIC REACTIONS IN THE FUEL CELL.

Unfortunately there are not yet empirical data of the consumption of LPG, the production of energy and CO_2 during the entire life of the SAPIENS system, so in this study they were estimated.

The estimation was done without consider the production of heat and assuming that:

- LPG is made of a higher percentage of propane (70%) than butane (30%);
- all the CO gas will entirely oxidise in CO_2 gas;
- any dispersion of material is present in the process.

The estimated quantity of LPG that will be used is 95 kg will give us a total energy of 450 MJ.

Conventional systems on a RV are powered by converting the kinetic energy produced during the movement of the RV. This means that the battery can be recharged during the drive and when the camper is stop, the recharging options are:

1. stop in a camp-site, where it is possible recharge the battery from the mains;
2. drive the RV approximately once a day in order to recharge the battery.

Conventional RV systems are composed of:

- alternator (battery charger);
- electrical system control box;
- copper wiring harness;
- solar charger;
- leisure battery;

- remote controller panel.

All these elements will be present on the RV with the SAPIENS APU, for this reason in, as written in the assumptions (section 4.1.3), they are kept out from the system boundary.

It has been estimated that the amount of diesel required to satisfy the FU by the idle engine system is equal to 162 litres of fuel.

4.2 LIFE CYCLE INVENTORY (LCI) ANALYSIS

During the LCI analysis all the data regarding both systems were collected, with a particular attention on the data about the mSOFC system, due to the particular materials and less knowledge of the production processes.

All the data were collected between in the period 2014-2015, with Europe as the geographical reference, due to the international nature of the project. Data collection comprehends both primary and secondary data. For the primary data, tailored-made questionnaires were prepared and distributed by IREC among the project partners, in order to collect data concerning the SOFC stack and BoP components, materials, their weight and the energy consumption for their production.

In order to fill possible gaps in the data collection, secondary data coming from available commercial database and literature was used.

4.2.1 DATA COLLECTION OF mSOFC APU SYSTEM

The data collection for the mSOFC APU system is related to the tubes production, the Hotbox components and the components comprising the BoP.

The size of the system being considered is a 16 tubes system, nominally producing 100 W. The mSOFC tubes are based on the LSCF/SDC/YSZ/Ni-YSZ configuration and produced by processes of high shear extrusion, coating and sintering of the Ni-YSZ anode supported tube. [11]

MANUFACTURING OF THE TUBES

The data regarding the materials and energy inflows and outflows to the process of manufacturing were supplied by Adelan and other partners.

Main tube production material inputs:

- Yttrium Stabilised Zirconia (YSZ) powder, with the composition of 13 weight percentage (wt%), was chosen for the supporting anode and for the electrolyte layers, made with finer particle size;
- green-Nickel oxide (NiO) powder, used for the anode and electrolyte layers;
- Lanthanum Strontium Cobalt Ferrite (LSCF) powder, commonly used for the cathode layer in SOFC.

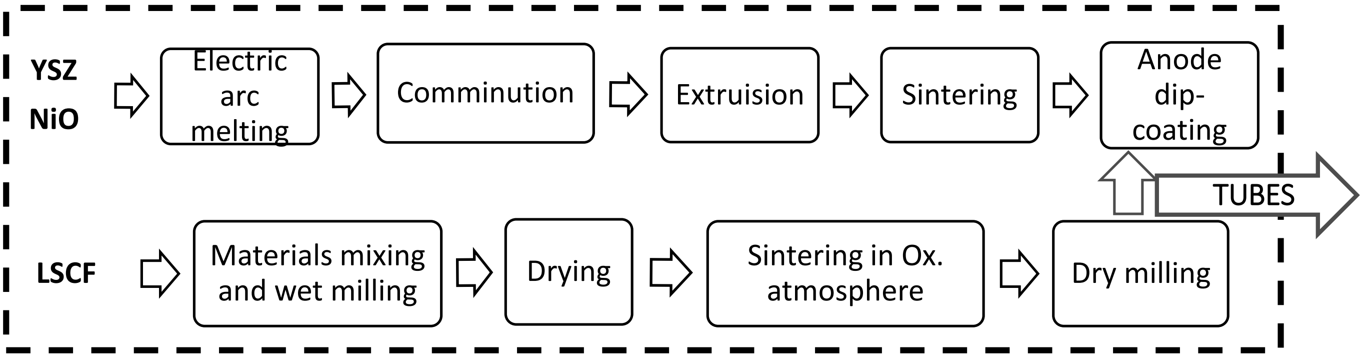


FIGURE 17 MICROTUBES-SOFC PRODUCTION CHAIN

The main tube production steps as represented in Figure 17 **Errore. L'origine riferimento non è stata trovata.** are:

1. Preparation of the YSZ/Ni material composition;
2. Preparation of the cathode material by a reaction sintering process;
3. Production of a thermoplastic feedstock containing both Y13 wt% and NiO;
4. Extrusion of the feedstock to tubes;

5. Thermal bindering of the extruded tubes and pre-sintering;
6. Cutting of the tubes to the target length;
7. Dip coating of the tubes with the electrolyte;
8. Co-sintering of the anode and the electrolyte;
9. Reduction of NiO in the anode to Ni using a reducing gas atmosphere in the furnace;
10. Coating of the sintered tube with the cathode material (LSCF).

Components	Materials	% of material in 1 tube
Cathode	Lanthanum	16.27 %
	Cobalt	2.50 %
	Ferrite	10.63 %
	Strontium	6.90 %
	Cathode Tot.%	36.30 %
Barrier layer	Samarium	0.01 %
	Cerium	0.49 %
	Barrier layer Tot.%	0.50 %
Anode	13%wt YSZ	36.57 %
	Nickel	18.15 %
	Other materials	8.48 %
	Anode Tot. %	63.20 %

TABLE 3 PERCENTAGE OF MATERIALS USED TO MANUFACTURE 1 TUBE (ROUGHLY 6 GRAMS)

Components	Processes	% of energy for 1 tube
LSCF	Preparation of the materials	2.90 %
Sm-doped ceria	Preparation of the materials	2.49 %
YSZ and Ni-YSZ	Preparation of the materials	5.45 %
Final tube	Sintering, extrusion and coating processes	89.16 %
	Tot. %	100.00 %

TABLE 4 PERCENTAGES OF THE ENERGY DEMANDED FOR MANUFACTURING 1 TUBE

INTERCONNECTIONS, HOTBOX AND BALANCE OF PALNT ASSEMBLY

The interconnections, the hotbox and the BoP assembly were conducted by Adelan and CUTEC.

The Hotbox and the Balance of Plant (BoP) were designed by CUTEC and Adelan, and include all the electronic components to control and manage the stack during normal performances.

Materials and energy inputs with small contribution to the overall inputs have been neglected. Materials with a relevant weight are PVC, stainless steel, steel and brass.

Components	Main material	Weight (gr)
Air blower	Steel	250
LPG flow controller	Brass	1200
CPOx air adjustment	Brass	1200
LPG pressure regulator	Steel	500
Sulphur trap	Stainless steel	500
Sulphur adsorbent powder	Cu/Mn powder	76.40
Controller (Raspberry Pi+ Tinker Forge)	Several materials, mainly plastic and metals	400
DC/DC converter 12→24 V	Several materials, mainly plastic and metals	40
Casing	PVC	3000
Tubing/piping	PVC	500
Heat exchanger/recuperator	Stainless steel	1200
Wires and ink	Silver	90
Manifold	Plastic ABS	25
Insulation	Polycrystalline wool	800
Reformer	Cordierite with Pt group metals	<1 mg

TABLE 5 INTERCONNECTION, HOTBOX AND BALANCE OF PLANT COMPONENTS USED IN A 16 TUBE SYSTEM

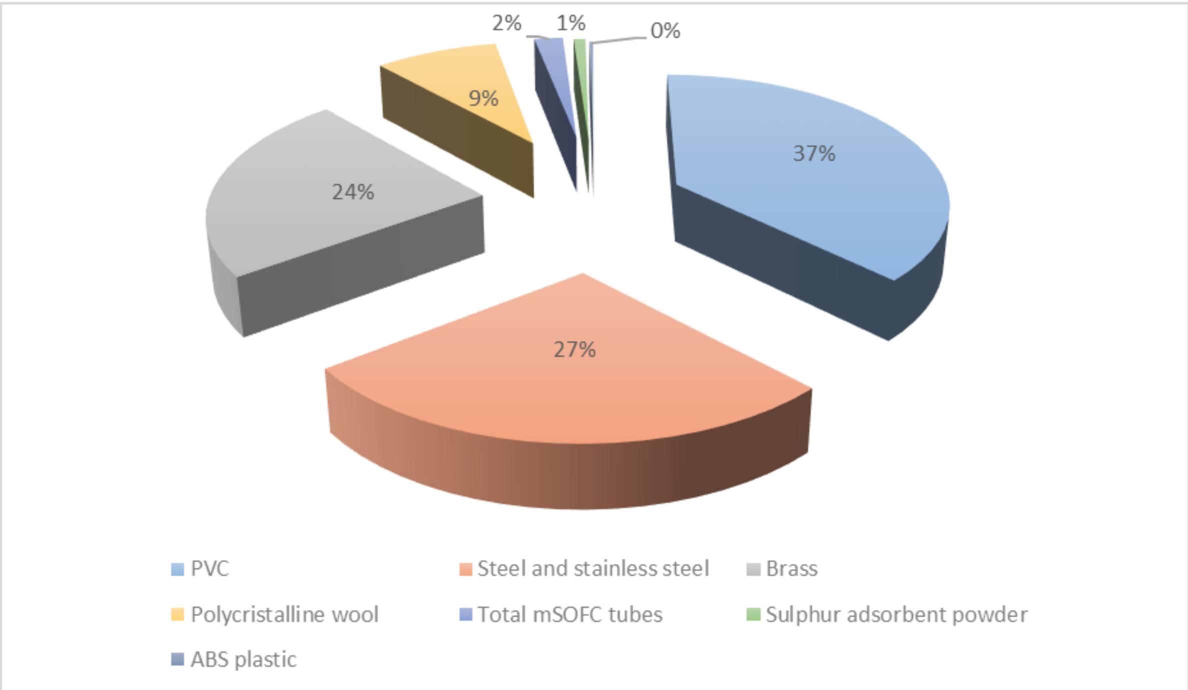


FIGURE 18 PERCENTAGES OF THE MATERIAL CONTRIBUTIONS TO THE BALANCE OF PLANT TOTAL WEIGHT

USE PHASE

Data related to the use phase come from estimation of the LPG utilised in a trip scenario of 3000 hours of system utilisation for the production of 450 MJ, with an efficiency of the entire system around 40%.

Components	Material	Weight
Auto-gas	LPG (70% propane, 30% butane)	94.41 kg
Auto-gas, for 1 start-up cycle	LPG (70% propane, 30% butane)	0.5 kg
Sulphur adsorbent	Mn-Cu adsorbent powder	76.4 gr

TABLE 6 AMOUNTS OF LPG AND SULPHUR ADSORBENT REQUIRED DURING THE USE PHASE OF THE SYSTEM

END-OF-LIFE (EoL)

In the End-of-Life phase we have to understand which kind of waste will result at the point of disposal and how to manage them.

The classification and the end-of-life pathways for most of the BoP components are known and legislation exists. In contrast, the EoL management of SOFC stacks is not well known and understood, due to the fact that fuel cells are a quite new technology and that the research for new materials is carrying on.

That means a lack in the legislation that can compromise the entry in the market for this technology, because there could be conflict with the requirements imposed by legislation, such as the European End-of-Life Vehicles Directive. [24]

The management of the EoL of SOFC system should follow the principles accepted at international level, defined by Agenda 21 [25] and reaffirmed in the directive 2008/98 EC [26]. This hierarchy is based on the reduction of the waste production at source, followed by reuse, recycling and disposal to landfill.

In addition during the design and production phase a proactive approach to the EoL management should be adopted. This would help the reduction of valuable and hazardous materials used in the stack, the emissions to the environment and an increasing use of recyclable materials [27].

For the lack of primary data relating to the EoL of the mSOFC system it was decided to model a scenario as much as possible similar to the one that might realise at the actual knowledge and following the European legislation concerning the hazardous wastes (Directive 2000/532/EC) and the Waste Electrical Electronic Equipment management (Directive 2012/19/EU).

- *mSOFC tubes End-of-Life management*

The mSOFC tubes EoL management depends on the technologies and economic cost to recycle Nickel.

The possible scenarios are two:

1. the optimistic and ideal one, the tubes do not present any damages and can be completely reuse. Unfortunately at the current state of art the Ni-ceramic anodes are not stable when hydrocarbon fuels are used, forming a large amounts of carbon deposition that leads to a degradation of the tubes and a lower performances, due to the block of the gas transportation and the production of some cracks in the anode [28];

2. in the real scenario, of the 2015 technical knowledge, the Nickel is oxidised and any industrial recover of the Nickel from the ceramic is possible, only a deposit of the tubes such as hazardous waste will be done.

As the tubes also the sulphur adsorbent powder and the CPOx catalyst have been classified as hazardous wastes; all the other elements in contact with the tubes should be analysed to find out the nickel contamination level, if present. For the study, all the components in contact with the tubes have been classified as not hazardous wastes.

- *BoP End-of-Life management*

In a scenario of return to manufacturer policy, the producer of the stack and BoP could reuse some components, if they were not contaminated, damaged or some changing in the BoP design. The possible components that could be reused are: the casing in PVC, the recuperator in stainless steel, the µ-PC and some valves and flow meters.

Otherwise all these components could be recycled like the others.

In this study it has been modelled the scenario displayed in Table 7.

	Recycling (%)	Landfilling (%)	Incineration (%)
Steel and stainless steel	60% (1.53 kg)	40% (1.02 kg)	-
Brass	60% (1.44 kg)	40% (0.96 kg)	-
PVC and ABS plastic	60% (2.11 kg)	10% (0.35 kg)	30% (1.06 kg)
Polycrystalline wool	50% (0.4 kg)	-	50% (0.4 kg)
Electronics components	40% (0.18)	-	60% (0.26 kg)

TABLE 7 END OF LIFE MANAGEMENT SCENARIO MODELLED FOR THE SYSTEM, EXCEPTED FOR THE TUBES

4.2.2 DATA COLLECTION OF CONVENTIONAL APU SYSTEM

The data of the traditional APU system were collected from Auto-Sleepers, which supplied a list of the system components that they build on the Recreational Vehicle (section 4.1.5).

The components comprising the conventional RV system:

- alternator (battery charger);
- electrical system control box;
- copper wiring harness;
- solar charger;
- leisure battery;
- remote controller panel.

As stated in the assumptions (section 4.1.3) all the common components between the two systems were taken out from the study. So, being all the ones in list common elements they have not been included in the study, as well as the engine for running the RV, whose the main function is still provide energy for the propulsion of the camper-van. For the conventional system, or idle engine system, the only elements considered is the diesel fuel, of which all the life cycle has been taken into account.

The quantity of diesel estimated for satisfying the functional unit is equal to 162 litres.

For calculating that fuel quantity, key parameters, such as power inverter efficiency [29], battery charger-discharge cycle efficiency [30], alternator efficiency [31] and idle engine diesel consumption [19] have been used.

Electrical system data	Power inverter efficiency	0.900 [29]
	Battery charger/discharger efficiency	0.750 [30]
	Alternator efficiency	0.704 [31]
Fuel/Energy consumption data	Idle engine diesel consumption	3.104 [19]
Fuel data conservation to energy units	Diesel engine volumetric density (MJ/kg)	38.600 [32]

TABLE 8 KEY PARAMETERS FOR THE CALCUALTION OF THE DIESEL USED FOR SATISFYING THE FU

4.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In Life Cycle Impact Assessment (LCIA) all the resources and emissions of the LCI are translated into environmental impact indicator of the potential impacts on the impact categories previously chosen.

LCIA results of the mSOFC APU system

In the following table (Table 9) the results for the system manufacturing, use phase, end of life and recycling for the life cycle of the mSOFC APU system under study are reported. Instead Figure 14 displays the relative percentages of the manufacturing, use and end-of-life phases, as it can be noticed the main contributions to the LCIA results come from the system production phase, that includes the fuel cell, hotbox and BoP manufacturing. Landfilling and transport, included in the EoL phase, do not have a high weight on the total LCIA results.

	Total system manufacturing	Total use phase	Total End of Life	TOTAL	Credit for the material recycling
ADP-elements (kg Sb eq.)	2.59E-01	1.14E-05	3.11E-06	**2.59E-01**	-1.50E-03
ADP-fossil (MJ)	4.04E+03	5.16E+03	1.88E+00	**9.20E+03**	-1.87E+02
AP (kg SO_2 eq.)	2.35E+00	4.00E-01	4.51E-04	**2.75E+00**	-2.04E-01
EP (kg phosphate eq.)	1.13E+00	2.30E-02	5.71E-04	**1.16E+00**	-1.81E-01
FAETP (kg DCB eq.)	2.44E+02	1.75E+00	2.97E-03	**2.46E+02**	-8.42E+01
GWP (kg CO_2 eq.)	3.63E+02	3.05E+02	2.63E+00	**6.70E+02**	-1.24E+01
HTP (kg DCB eq.)	5.39E+02	1.16E+01	1.72E-04	**5.50E+02**	-3.68E+02
MAETP (kg DCB eq.)	7.18E+05	5.14E+03	-5.18E+02	**7.23E+05**	-1.32E+05
ODP (kg CFC-11 eq.)	7.29E-06	1.86E-09	-2.33E-08	**7.27E-06**	-1.59E-07
POCP (kg ethane eq.)	1.52E-01	6.39E-02	-1.32E-05	**2.16E-01**	-1.24E-02
TETP (kg DCB eq.)	2.38E+00	1.07E-01	2.99E-03	**2.49E+00**	-6.86E-01
Primary Energy (MJ)	7.45E+03	5.19E+03	4.88E-02	**1.26E+04**	-2.20E+02

TABLE 9 LCIA RESULTS FOR THE SOFC SYSTEM

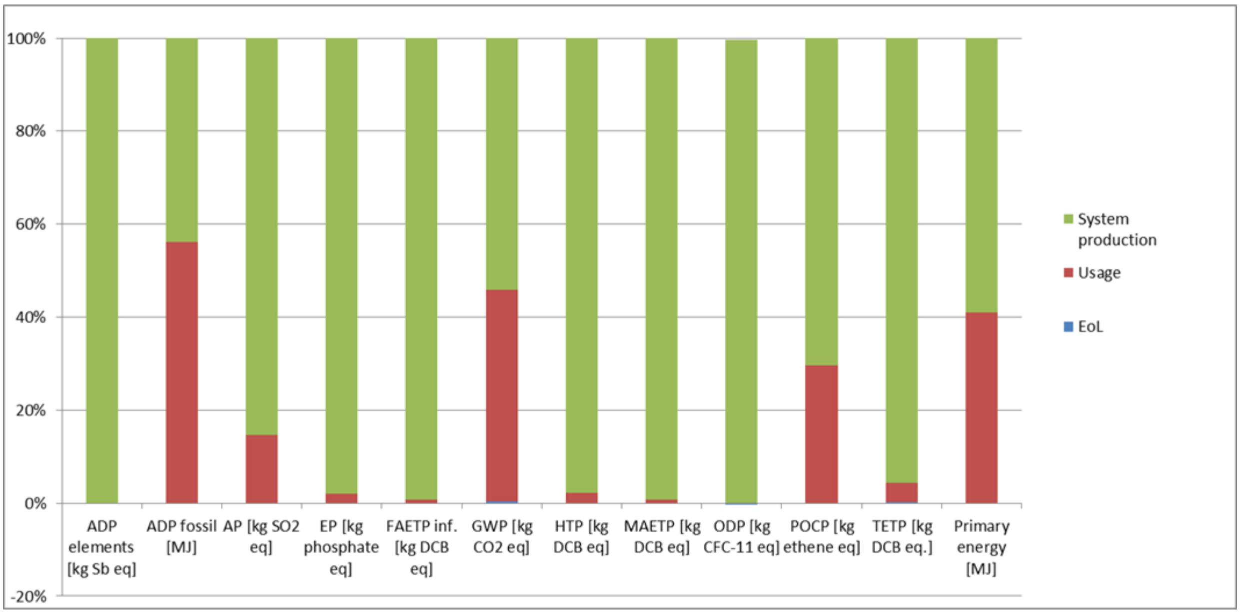


FIGURE 19 CONTRIBUTIONS OF THE LIFE STAGES OF THE SOFC SYSTEM TO THE LCIA RESULTS

For understanding the relevance of each impact indicator among the other indicators, a normalisation has been performer, where normalisation references are calculated as the background impact over the course of one year per person in the area for which the impact is computed. This gives the normalisation references the unit “impact potential per person per year” for each individual impact category, using the method EU25+3, year 2000 (person equivalents). The results of it (see Figure 20) highlight that the Abiotic Depletion Potential (ADP-elements) and the Marine Aquatic Ecotoxicity Potential (MAETP) are the two most relevant impacts.

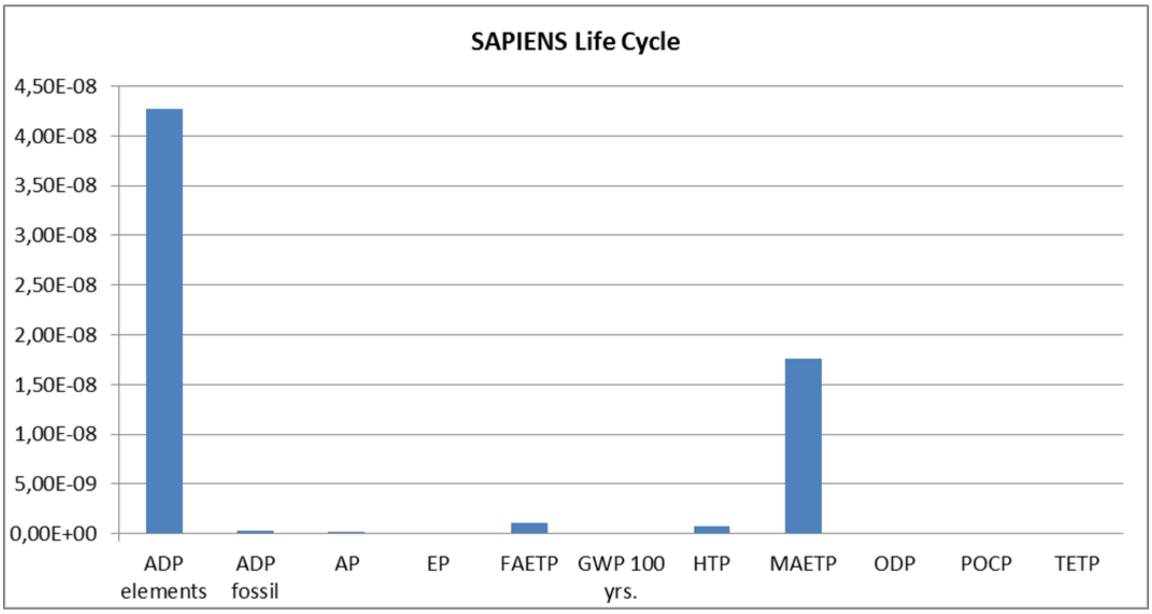


FIGURE 20 TOTAL NORMALISED VALUES FOR THE SOFC SYSTEM

Conventional RV system impact assessment

The impact assessment for the camper-van has been calculated only for the categories: Global Warming Potential (GWP) and the Primary Energy demand.

	Primary energy consumed (MJ)	Global Warming Potential (kg CO_2 eq.)
Diesel life cycle	7.51E+03	5.55E+02

TABLE 10 LCIA RESULTS FOR THE RECREATION VEHICLE SYSTEM

As stated in the assumption the results have been calculated only for the life cycle of the diesel quantity (162 litres) used to satisfy the FU (450 MJ).

4.4 INTERPRETATION OF THE RESULTS

In this section the results described in the section 4.3 are interpreted with a focus on the elements contributing the most to the environmental impacts. To accomplish the interpretation phase the impacts of the elements with a high weight on the total result have been chosen and analysed deeply carrying out sensitivity and uncertainty analysis.

mSOFC APU system results interpretation

The results (see section 4.3) presents that the life phase with the highest weight on the overall results is the manufacturing phase. The elements reported in Figure 21 are the ones detected being the ones with the highest values of impacts.

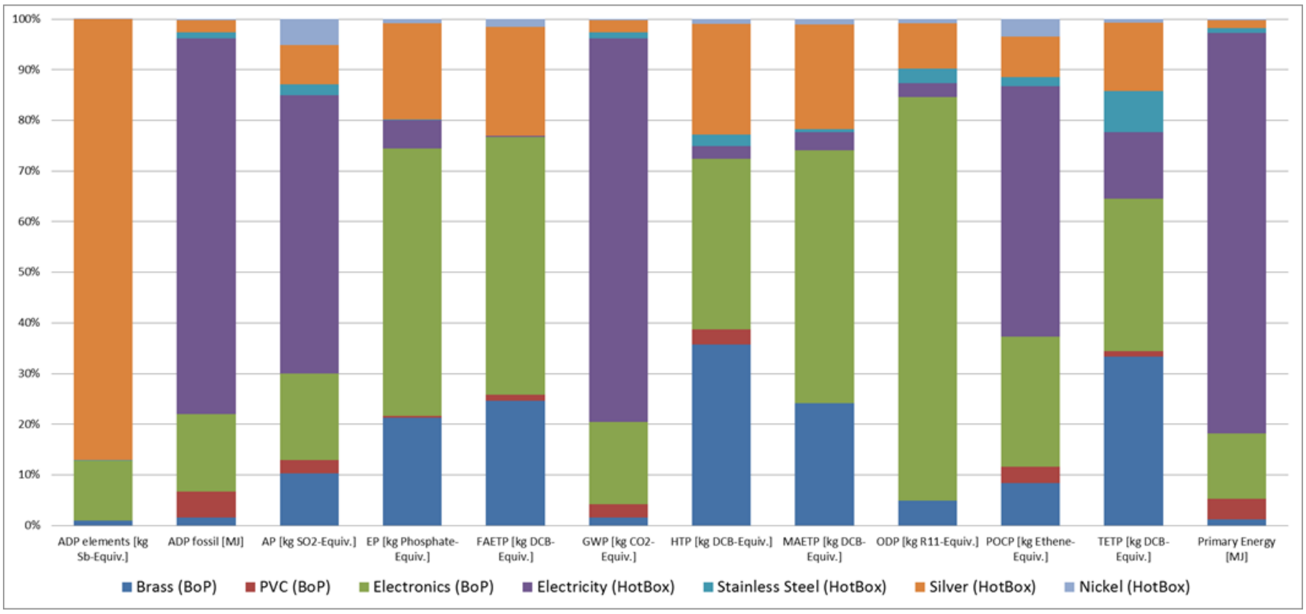


FIGURE 21 CONTRIBUTIONS TO THE LCIA RESULTS OF BoP AND HOTBOX ELEMENTS

As it can be observed the ADP-elements category is influenced by the silver use, instead the results of the fossil resourced depletion (ADP-fossil), the GWP and the primary energy depend from the electricity used in the tubes and for some material production.

The ADP-elements and the MAETP categories, presenting the highest values in the normalisation results have been influenced, for the most part, by the silver, electronics components and brass flows. Instead the electricity has been a relevant flow for the categories: primary energy, GWP and ADP-fossil.

In spite of their not high weight the electronics components have one of the most significant impact on the LCIA results, this is caused by the fact that they are made of printed circuit boards, containing different materials, such as plastic, copper and precious metals.

Comparative results interpretation

In this part a comparison between the two systems is presented. The two categories used to set the comparison are the primary energy demanded (MJ) and the Global Warming Potential (GWP, kg of CO_2 eq.), due the fact that they are the only two impact categories examined for the conventional diesel idle engine system.

The results of Table 11 display the primary energy and the GWP emitted by the production, combustion of the two types of fuel used. Looking them it can be assumed that the diesel for the idle engine requests a higher quantity of primary energy than the LPG used in the mSOFC APU system. This is reflected, also, in the GWP emissions.

	Primary energy consumed (MJ)	Global Warming Potential (kg CO_2 eq.)
Diesel, for the conventional idle engine system	7.51E+03	5.55E+02
LPG, for the mSOFC APU system	5.19E+03	3.05E+02

TABLE 11 COMPARISON BETWEEN THE DIESEL AND LPG USED IN THE 2 SYSTEMS COMPARED

Moreover, the amount of emissions calculated affecting the GWP impact category of the entire life cycle, of the mSOFC system, is around 670 kg of CO_2 eq., only 120 kg more than the use phase of the conventional diesel idle engine system.

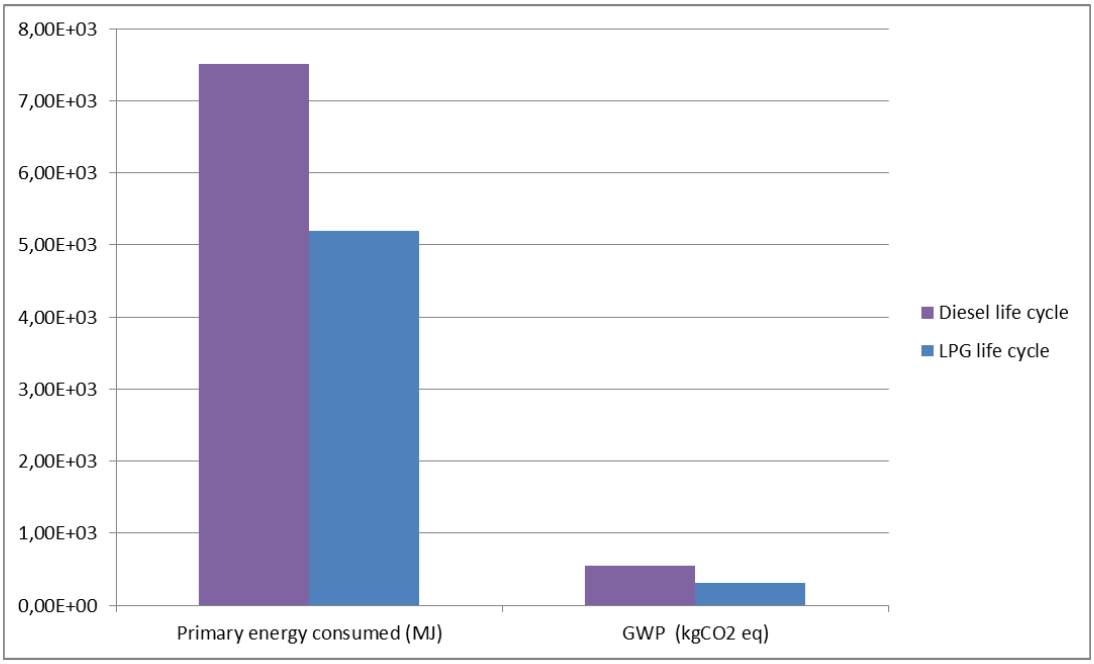


FIGURE 22 COMPARATIVE RELATIVE RESULTS OF THE PRIMARY ENERGY AND THE GWP

Sensitivity analysis of the mSOFC APU system

The sensitivity analysis can detect which of the parameters defined in the mSOFC system model are more significant for the total result calculation.

The analysis has been performed for the mSOFC APU system model, and all the parameters relating to the mass and the energy have been made to vary in a range between ± 100 %.

For the analysis three impact categories have been chosen:

1. Abiotic Depletion Potential-elements (ADP-elements);
2. Marine Aquatic Ecotoxicity Potential (MAETP)

   For their highest values in the normalisation analysis and

3. Global Warming Potential (GWP).

	ADP-elements variation
Silver wires parameter	87.60 %
Electronics components parameter	11.90 %
	MAETP variation
Electronics components parameter	56.50 %
Silver wires parameter	23.60 %
Weight of the air adjustment parameter	11 %
	GWP variation
System energy production parameter	42.30 %
Manufacturing electricity parameter	28.10 %
Electronics components parameter	8.83 %

TABLE 12 SENSITIVITY RESULTS FOR THE SOFC APU SYSTEM (WITH VALUES>5%)

The sensitivity results in Table 12 confirm the silver as the element with the highest influence on the ADP category, and that the MAETP results depending from the electronics components.

Uncertainty analysis

The uncertainty analysis is useful to understand which the confidence of the LCIA results is. The method used is the Monte Carlo and the variation range chosen is equal to ± 20 %.

The impact categories undergo the Monte Carlo analysis are the ones chosen for the sensitivity analysis (ADP-element, MAETP and GWP); at the same the elements object of the analysis are the silver wires and the electronics components.

The uncertainty analysis has been launched using the GaBi software, the results reported take into account the 95% of the confidence.

- *UNCERTAINTY OF THE ADP-elements INDICATOR*

Parameter	Initial value	Variation	ADP mean result	Uncertainty range (95 % confidence)
Silver wires parameter	90 g	±20.00 %	0.258 kg Sb eq.	±9.25E-02
Electronics components parameter	400 g			

TABLE 13 MONTE CRALO SETTINGS AND RESULTS FOR ADP-ELEMENTS

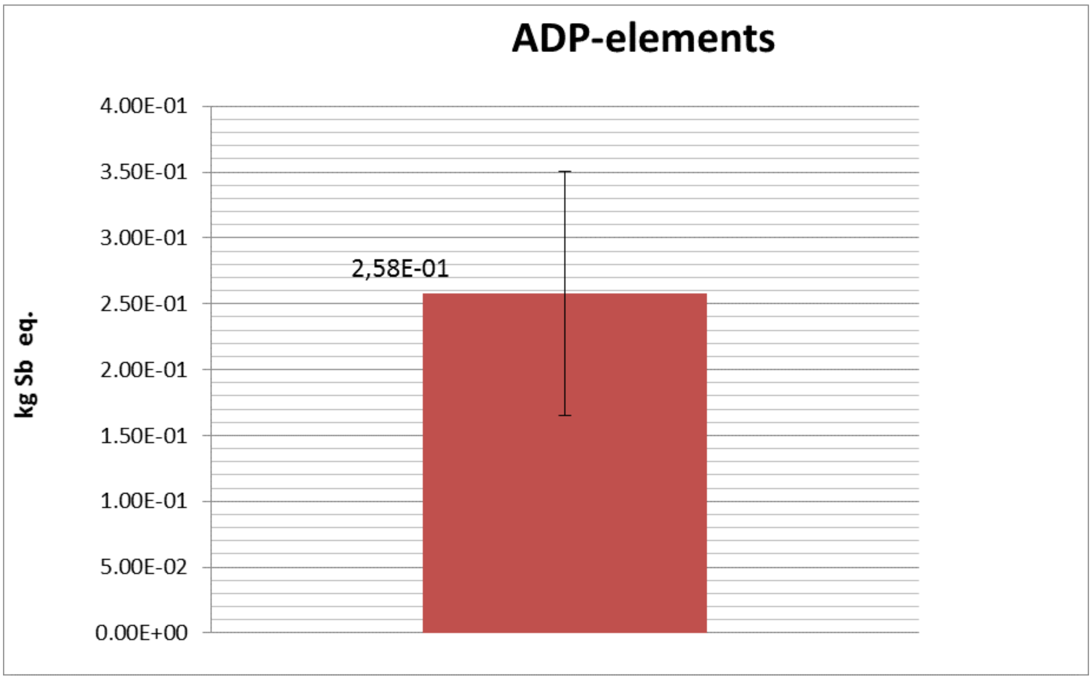


FIGURE 23 ADP-ELEMENTS RESULTS WITH UNCERTAINTY RANGE

- *UNCERTAINTY OF GWP INDICATOR*

Parameter	Initial value	Variation	GWP mean result	Uncertainty range (95 % confidence)
Silver wires parameter	90 g	±20.00 %	718 kg CO_2 eq.	±2.55E+01
Electronics components parameter	400 g			

TABLE 14 MONTE CARLO SETTINGS AND RESULTS FOR GWP

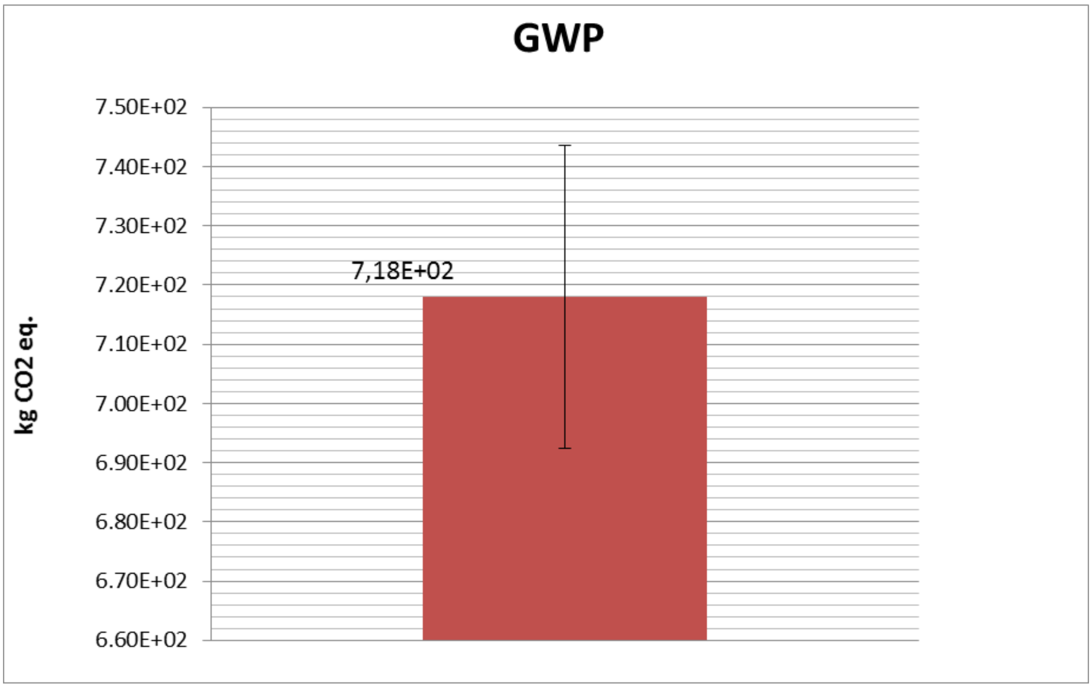


FIGURE 24 GWP RESULTS WITH UNCERTAINTY RANGE

- *UNCERTAINTY OF MAETP INDICATOR*

Parameter	Initial value	Variation	MAETP mean result	Uncertainty range (95 % confidence)
Silver wires parameter	90 g	±20.00 %	7.84e+05 kg DCB eq.	±1.87E+05
Electronics components parameter	400 g			

TABLE 15 MONTE CARLO SETTINGS AND RESULTS FOR THE MAETP

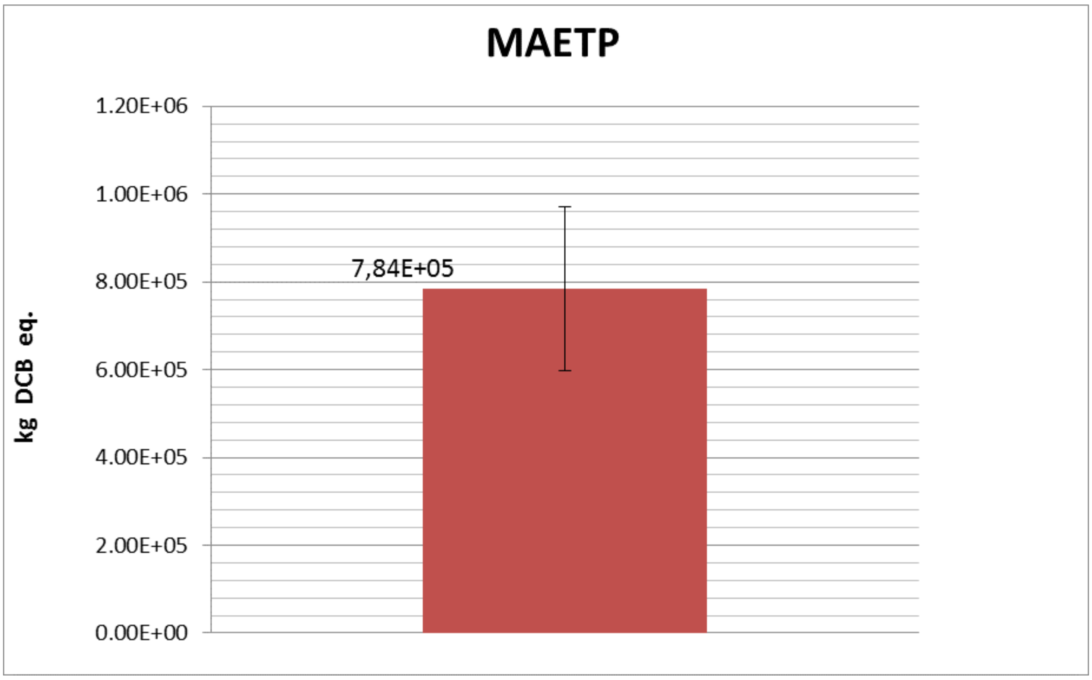


FIGURE 25 MAETP RESULTS WITH UNCERTAINTY RANGE

Additionally, an uncertainty analysis only for the results of the use phase of the LPG has been carries out; in this case the categories considered are the Primary Energy and the GWP, used to make possible the comparison with the results of the conventional diesel idle engine.

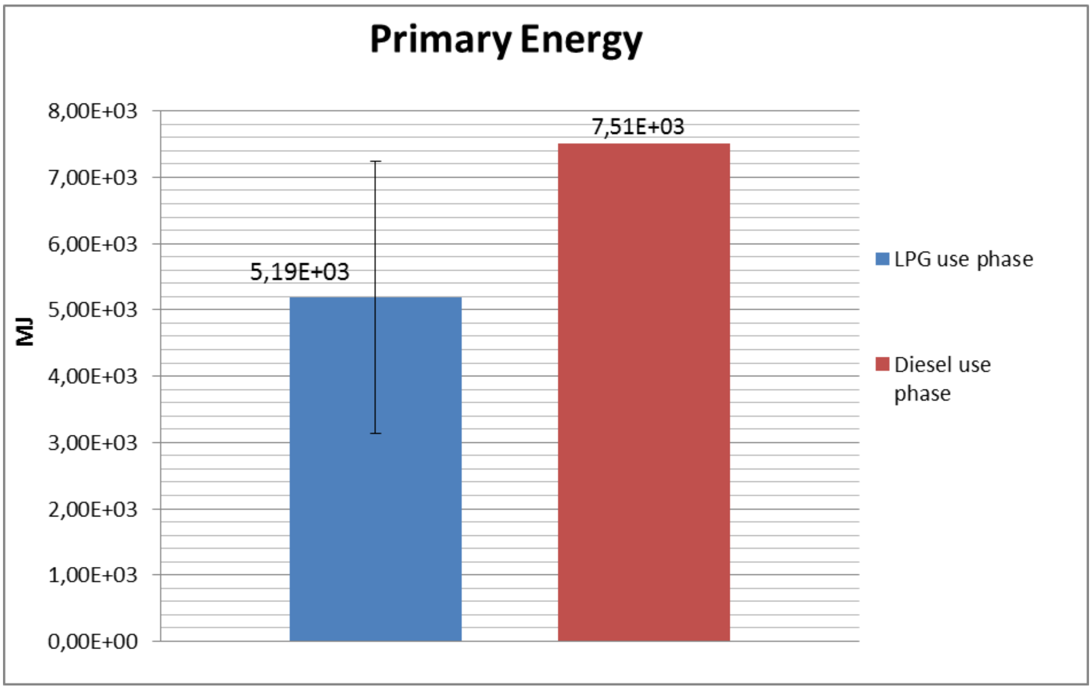


FIGURE 26 COMPARISON BETWEEN THE PRIAMARY ENERGY REQUIRED BY THE SOFC SYSTEM IN THE USE PHASE AND THE PRIMARY ENERGY REQUIRED IN THE USE PHASE OF THE CONVENTIONAL DIESEL IDLE ENGINE

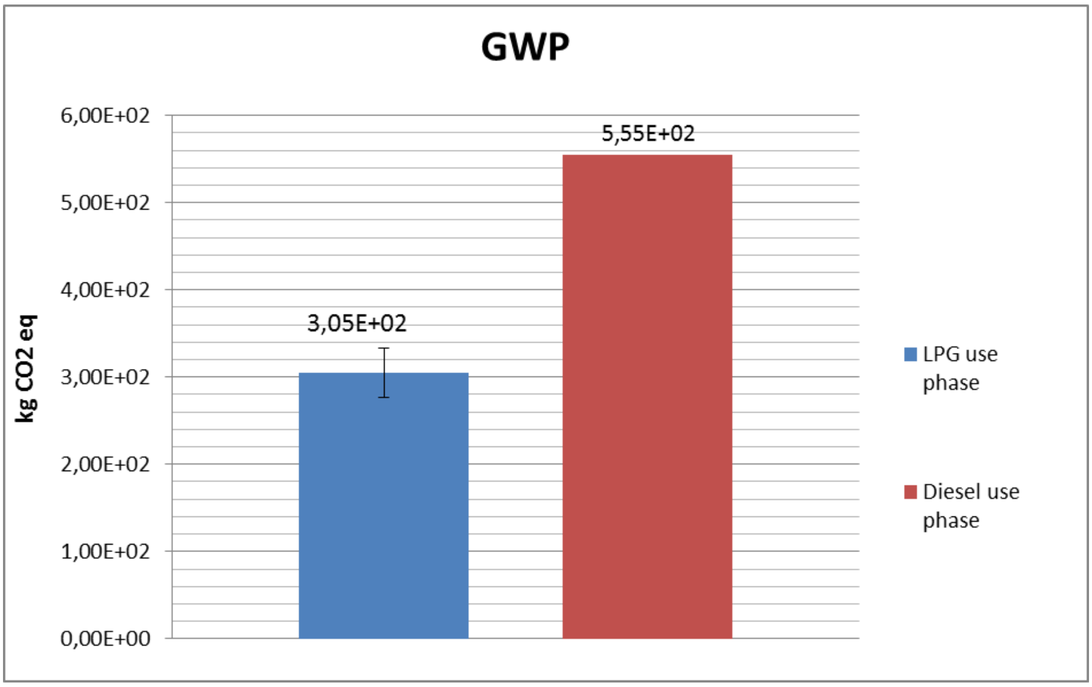


FIGURE 27 COMPARISON BETWEEN THE CONTRIBUTION TO THE GWP OF THE SOFC SYSTEM AND THE CONVENTIONAL DIESEL IDLE ENGINE DURING THEIR USE PHASE

Figure 26 and Figure 27 show the variations of the Primary Energy and GWP in the use phase of the LPG used in the mSOFC APU system, and display if the variation were significant compared to the results (from the LCIA) of the diesel idle engine.

In the first figure (Figure 26) the result relating the Primary Energy uncertainty of the LPG may be lower than the amount of energy demanded by the diesel system, besides the variation of the LPG value is quite relevant.

Instead, in the second figure (Figure 27) referring the GWP it is clear that its variation is not so relevant; in fact the value is still lower than the GWP result of the diesel idle engine.

5 CONCLUSIONS

The LCA analysis concerning the SAPIENS project reveals the overall environmental impacts of the microtubular solid oxide fuel cell APU system, and the results relating the comparative analysis set with the conventional idle engine technology, commonly used in the RV.

The study has taken place in the period 2014-2015, following the standardised approach suggested for the LCA studies:

1. definition of the goal and scope of the analysis;
2. Life Cycle Inventory (LCI);
3. Life Cycle Impact Assessment (LCIA);
4. interpretation of the results obtained.

The data collected for the mSOFC APU system refer mainly to 2014 project development, and were gathered from the several Consortium partners by questionnaires.

Instead, the data for the traditional idle engine system for recharging the RV leisure battery were taken, mainly, from literature.

The functional unit of the study was chosen as the energy demanded to satisfy a trip scenario of 3000 hours that correspond to 450 MJ; using this as a comparative base the GWP emissions and the primary energy request for the use phase of the two systems, were compared.

Modelling and calculation for the entire life cycle of the mSOFC APU system were done using GaBi 6, a professional software developed to Thinkstep, and using as source of background data commercial databases such as Thinkstep international database and Econinvent 2.2.

Generally, the analysis shows up that the life cycle phase having the highest outputs and impacts is the stage of production of the system, in which the tubes manufacturing and the assembly of the stack and the balance of plant take place.

The use phase, in which the fuel in the main input, has not a relevant contribution on the environmental impacts; in fact the only categories with a significant output are the Abiotic-fossil Depletion Potential (about 56% of the total) and the Global Warming Potential (around 46%).

In absolute the Abiotic-elements Depletion Potential (ADP-elements) in the category most affected by the production of the system, that because of the inputs of several materials for the tubes manufacturing and the BoP construction. Despite of the use of Nickel, the silver is the element whit the most relevant contribution to the ADP outcomes (around 87%). Another element with a significant weight on the outputs is the electricity used for manufacturing the tubes, whose impacts are quite high for the fossil ADP (Abiotic-fossil Depletion Potential), AP (Acidification Potential), GWP (Global Warming Potential), POCP (Photochemical Ozone Creation Potential) and the Primary Energy categories, with percentages going from 49% to 76%.

Furthermore, a sensitivity and uncertainty analyses were run.

The results of the sensitivity analysis for the Abiotic-elements Depletion Potential, the Marine Aquatic Ecotoxicity Potential and the Global Warming Potential have confirmed that the silver wires, the electronics components and the electricity production still have the highest percentages of contributions to the environmental impacts.

The comparison between the mSOFC APU system and the diesel idle engine system have been done using the two impact categories: Primary Energy consumption (MJ) and Global Warming Potential (GWP, kg of CO_2 equivalent) and considering the use phase of the mSOFC APU and the diesel life cycle of the idle engine system.

The outcomes, coming from the comparison, reveal that using LPG (Liquid Petroleum Gas) as a fuel implies a lower Primary Energy demand, and a lower GWP output than using diesel. In fact, the diesel life cycle produces an amount of 555 kg of CO_2 eq.

against the 305 kg emitted during the LPG life cycle, and the 670 kg emitted for the entire life cycle of the mSOFC APU system.

Moreover, the uncertainty analysis of the LPG used for the Primary Energy and GWP values has been done; the method chosen was the Monte Carlo, and the variation was set in the rage of ±20%.

Then, the results of the uncertainty analysis have been compared with the values of the Primary Energy and GWP of the use phase of the diesel conventional system. The comparison points out that a possible variation of the Primary Energy demand of the LPG in the use phase may reach the same value of Primary Energy consumption for the diesel, despite that the GWP linked to the LPG keeps having a significant lower value than the diesel output of GWP.

At the end of this work, it can be stated that the main efforts to cut down the environmental impact of the technology investigated (mSOFC APU system), should be focused on the reduction of energy requested during the manufacturing phase. It has to be remembered that the results have come from data related to a laboratory production scale, and that it is quite possible that once the production will be scaled up at industrial level the energy, as well as the materials, requirements will decrease and, as a consequence, the environmental impacts.

In spite of the results of the LCA do not highlight the end of life issue of the SOFC, that is still be an important argument of concern, due to the content of nickel, that at the state of knowledge it cannot be recovered from the ceramic materials and whose oxidation made the ceramic material not reusable for the same purpose.

6 REUSE, RECYCLE AND DISPOSAL RECOMMENDATIONS

The EoL management is one of the most important issues concerning the new technologies. This because it may happen that during the phases of research and development the EoL of the products is not evaluated, as much as it would be.

The undervaluation comes from a not proactive approach during the design phase in which it should be a good behaviour trying to:

- select not toxic materials;
- reduce the materials volume;
- select materials that could be reused and recycled [27].

This problem is present also in the fuel cells sector where the EoL issue has not been present in a practical way yet, due to the not wide entrance of the technology in the market.

In this study of LCA we tried to take account of a possible scenario following the EU legislation and the current known paths of reusing, recycling and disposal of the materials used in the system.

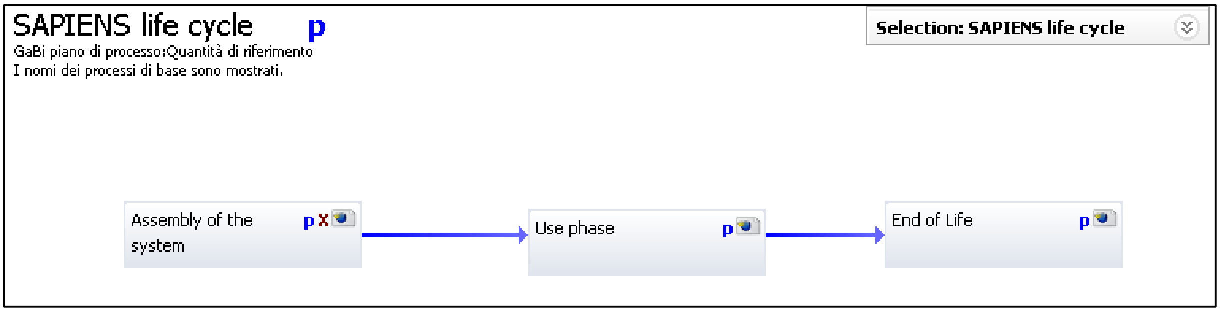
During the modelling of the End of Life phase the main concern was not linked with the materials presented in the high percentage, such as PVC and steel, because their EoL management procedures are known, but it was linked with the tubes EoL management, cause the content of nickel oxide, and the actual impossible industrial recover of it.

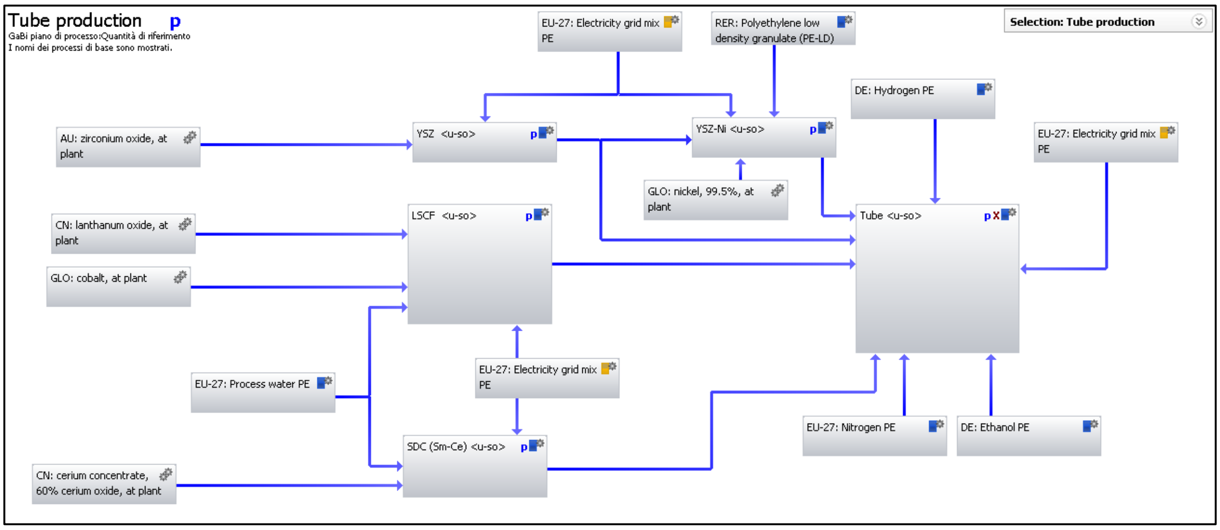
The most positive solutions would be to discover others no toxic and low impact materials that can replace the Ni in the cells, these would have the same catalytic features of Ni, such as good electrical conductivity, and maybe have a higher tolerance to carbon deposition [28].

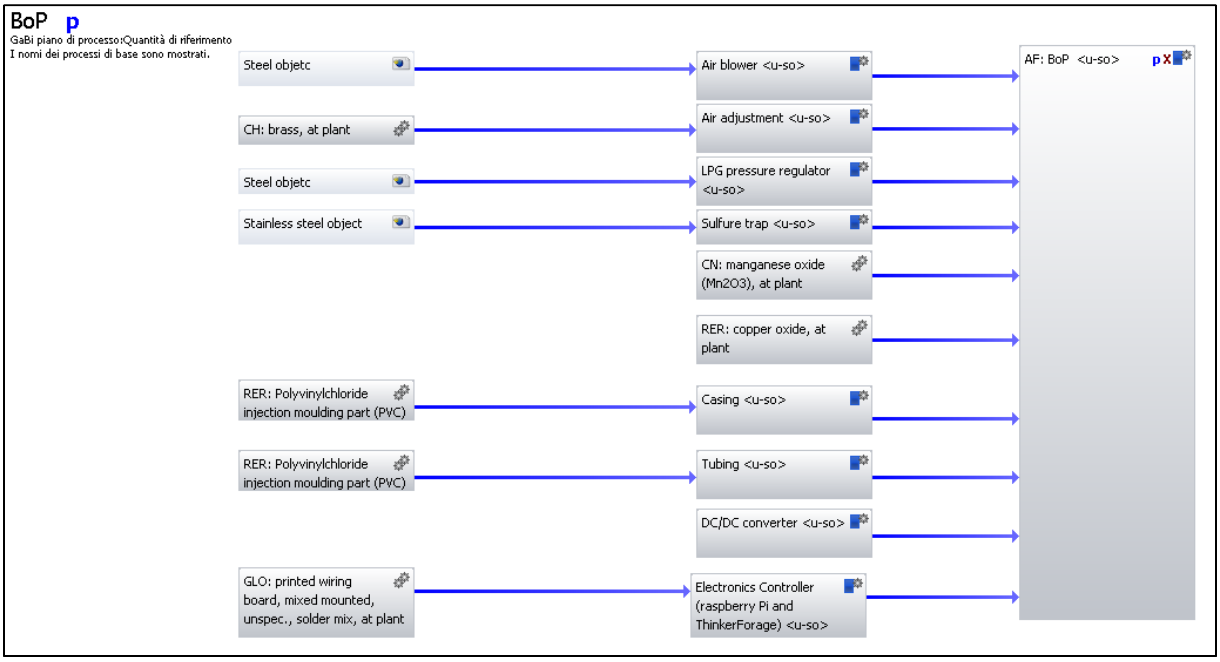
For the moment just the copper and the copper alloy have been individuated as possible replace materials in the SOFC anode [28]. This is due to their good electrical conductivity and low activity with hydrocarbons.

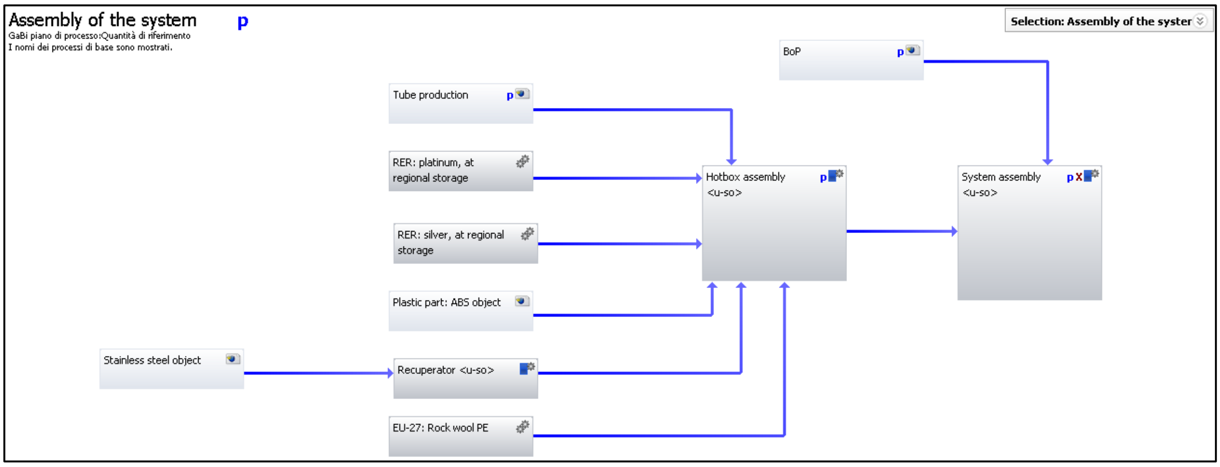
Otherwise the other solution it would be the recovering of NiO from the ceramic.

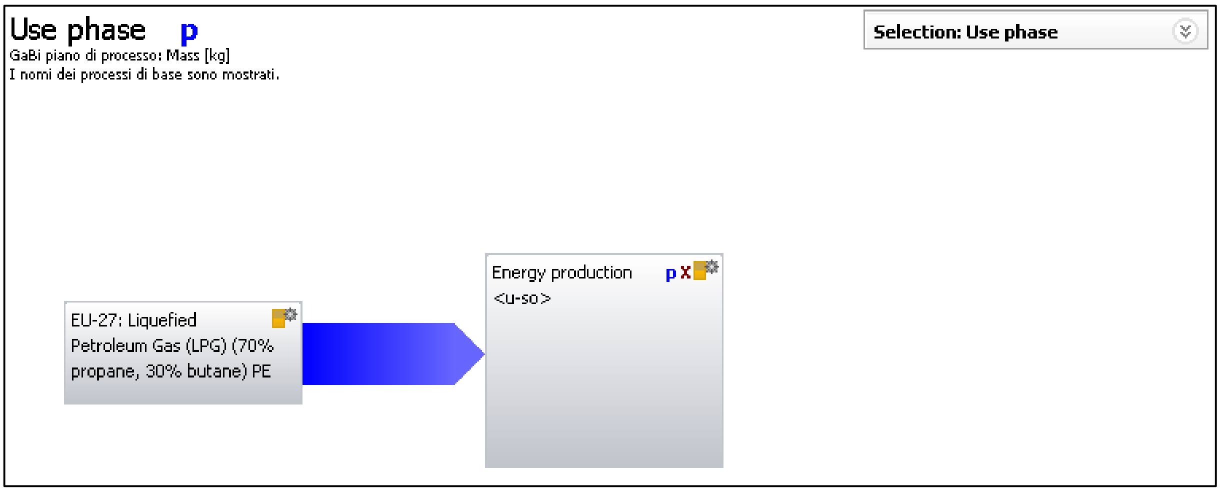
Unfortunately, there are not yet industrial processes allowing the recovering of it from the ceramic support, even if some studies about its recovering from secondary resources have been done. An interesting one explored the kinetic of the leaching with sulphuric acid from spent NiO catalyst [33]. The study was concentrated to the leaching from a spent catalyst made for the most of Al, the results were very positive with a 94% of NiO recovered. Maybe in the future this methodology could be used in industrial process on a ceramic matrix.

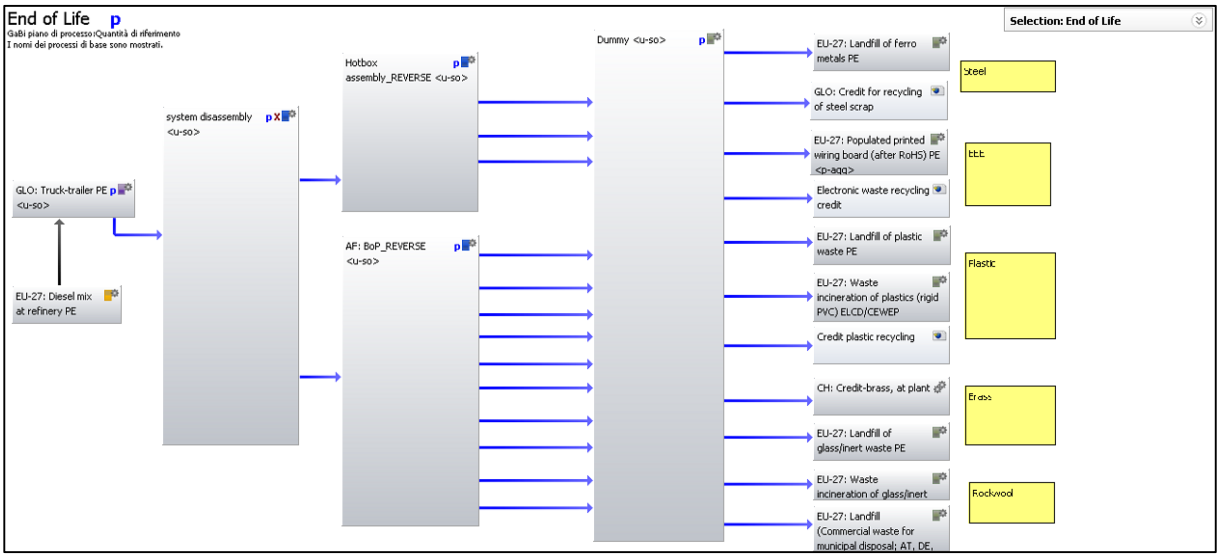

SAPIENS life cycle p
GaBi piano di processo:Quantità di riferimento
I nomi dei processi di base sono mostrati.
Selection: SAPIENS life cycle
Assembly of the system
Use phase
End of Life


Tube production p
GaBi piano di processo:Quantità di riferimento
I nomi dei processi di base sono mostrati.
Selection: Tube production
EU-27: Electricity grid mix PE
RER: Polyethylene low density granulate (PE-LD)
DE: Hydrogen PE
EU-27: Electricity grid mix PE
AU: zirconium oxide, at plant
YSZ <u-so>
YSZ-Ni <u-so>
GLO: nickel, 99.5%, at plant
CN: lanthanum oxide, at plant
LSCF <u-so>
Tube <u-so>
GLO: cobalt, at plant
EU-27: Process water PE
EU-27: Electricity grid mix PE
SDC (Sm-Ce) <u-so>
EU-27: Nitrogen PE
DE: Ethanol PE
CN: cerium concentrate, 60% cerium oxide, at plant


BoP p
GaBi piano di processo:Quantità di riferimento
I nomi dei processi di base sono mostrati.
Steel objetc
CH: brass, at plant
Steel objetc
Stainless steel object
RER: Polyvinylchloride injection moulding part (PVC)
RER: Polyvinylchloride injection moulding part (PVC)
GLO: printed wiring board, mixed mounted, unspec., solder mix, at plant
Air blower <u-so>
Air adjustment <u-so>
LPG pressure regulator <u-so>
Sulfure trap <u-so>
CN: manganese oxide (Mn2O3), at plant
RER: copper oxide, at plant
Casing <u-so>
Tubing <u-so>
DC/DC converter <u-so>
Electronics Controller (raspberry Pi and ThinkerForage) <u-so>
AF: BoP <u-so>


Assembly of the system p
GaBi piano di processo:Quantità di riferimento
I nomi dei processi di base sono mostrati.
Selection: Assembly of the syster
BoP
Tube production
RER: platinum, at regional storage
RER: silver, at regional storage
Plastic part: ABS object
Stainless steel object
Recuperator <u-so>
EU-27: Rock wool PE
Hotbox assembly <u-so>
System assembly <u-so>


Use phase p
GaBi piano di processo: Mass [kg]
I nomi dei processi di base sono mostrati.
Selection: Use phase
EU-27: Liquefied Petroleum Gas (LPG) (70% propane, 30% butane) PE
Energy production <u-so>


End of Life p
GaBi piano di processo:Quantità di riferimento
I nomi dei processi di base sono mostrati.
Selection: End of Life
GLO: Truck-trailer PE <u-so>
EU-27: Diesel mix at refinery PE
system disassembly <u-so>
Hotbox assembly_REVERSE <u-so>
AF: BoP_REVERSE <u-so>
Dummy <u-so>
EU-27: Landfill of ferro metals PE
GLO: Credit for recycling of steel scrap
EU-27: Populated printed wiring board (after RoHS) PE <p-agg>
Electronic waste recycling credit
EU-27: Landfill of plastic waste PE
EU-27: Waste incineration of plastics (rigid PVC) ELCD/CEWEP
Credit plastic recycling
CH: Credit-brass, at plant
EU-27: Landfill of glass/inert waste PE
EU-27: Waste incineration of glass/inert
EU-27: Landfill (Commercial waste for municipal disposal; AT, DE,
Steel
Plastic
Brass
Rockwool

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